HAMILTON HARBOUR STUDY 1974

november, 1975

Ministry
of the
Environment

Ontario

The Honourable
George A. Kerr, Q.C.,
Minister

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HAMILTON HARBOUR STUDY
1974

Water Resources Branch
Ontario Ministry of the Environment
135 St. Clair Avenue West
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November, 1975

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HAMILTON HARBOUR STUDY

1974

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INTRODUCTION

In 1972-73, the Ontario Ministry of the Environment under-
took a water quality study of Hamilton Harbour. The study
objectives were: to determine existing water quality and
its trends over recent years; to identify water quality
problems and recommend corrective measures; and to determine
the effects of landfilling on water quality. One of the
recommendations of that study was that artificial destrati-
fication be considered as a means of improving harbour water
quality. Artificial mixing will commence in June 1975.

The purpose of this report is to provide further information
on the water quality, including 1974 data, to provide a
literature survey and comment on other artificial mixing
experiments and to indicate the expected results of the
artificial destratification experiment in Hamilton Harbour.
The report format is similar to that of the 1974 report with
the subject matter broken down into components; each is
presented in technical detail in appendices and integrated
in the following text. The sections are as follows:

A.   Water Quality Update - 1974.
B.   Sediment Statistical Analysis.
C.   Dispersion.
D.   Periodicities and Mass Exchange through Burlington Ship
      Canal.
E.   Sediment Dissolved Oxygen Uptake.
F.   Phytoplankton.
G.   Artificial Mixing and Water Quality in Hamilton Harbour

As this is essentially a follow-up to the report released in
May, 1974, certain relevant sections of that report have
been reprinted in Section H for ready reference. In Section
H, one finds the description of the harbour, purpose of the
previous study, study outline, summary and findings, recommenda-
ations and further studies. Section I is a summary of the
proposed water quality surveys for 1975-7.

DISCUSSION

A. Water Quality Update - 1974

The water quality survey program in 1974 consisted of collect-
ing surface and bottom water samples four times at six
different locations as well as operating six recording
chemistry and current meters for a period of several weeks.
While these surveys were limited, some observations can be

made. Ammonia (nitrogen) levels continued to decrease from 1972 to 1974 and are now generally within the Ministry of the Environment public surface water supply criteria of 0.5 mg/l as N. Total phosphorus did not change significantly from 1972 to 1974. Although soluble phosphorus and chlorophyll a concentrations in July and October appear lower in 1974 than 1972, the available data were not adequate to quantify this observation. Analysis of the data from the recording chemistry meters confirmed the extent of the dissolved oxygen depletion as well as its variation. The calibration of the recording chemistry meters was checked with in situ volume samples. Severe dissolved oxygen depletion was evident in the hypolimnion of an offshore location (20m depth) in the eastern end of the harbour. During a strongly stratified period, July 11 to July 21, 1974, daily mean values of dissolved oxygen were less than 2.5 mg/l with a minimum value of 0.6 mg/l measured on July 13. The 1972 survey showed the dissolved oxygen depletion to vary widely in the Windermere basin between successive weeks. This variation is confirmed by the recording chemistry meter results which showed the standard deviation of dissolved oxygen to be 20 percent of the mean value in the Windermere basin. This variation appears to be a function of the Hamilton Pollution Control Plant operation combined with variable natural assimilative characteristics of the harbour. Counts for total coliform and enterococci are generally lower in 1974 than in 1972 but the sample size is too small to assess the change statistically. Fecal coliform counts were about the same in 1974 as in 1972.

B. Sediment Statistical Analysis

In the 1974 report, it was stated that the heavy metal discharges should be identified and action taken to reduce these discharges. A statistical correlation matrix method of relating bottom sediments by the ratios of trace metal and PCB content has been developed and applied to the data from the 1972 surveys. Details of the method, including the computer program which has some general applications (e.g. analyses which involve diversities) are contained in Section B. Results of the analyses indicate that generic relationships exist for the sediment in the eastern portion of the harbour (adjacent to the Burlington Skyway) and the northeast shore. This suggests that sediment chemistry is related to the same source, probably the Hamilton Pollution Control Plant outfall.

C. Dispersion

The dispersion coefficients used in the numerical model were transposed from other lake experiments. Consequently, a series of limited multiple drogue tracking experiments were

carried out in 1974 to validate the range of dispersion coefficients used. As a function of time, the measured dispersion coefficient behaved in a manner similar to that in other Great Lakes studies; the value of 1.2×10^4 cm^2/sec used in the numerical model was shown to be satisfactory.

D. Hamilton Harbour Periodicities and Mass Exchange Through the Burlington Ship Canal

In the previous report the harbour periodicities in both movement and water chemistry were found to be of prime importance in the interpretation of trends in water quality, process analysis and the application of a numerical model. In 1974, six recording current and chemistry meters were operated in the harbour to confirm this observation. The periodicities discussed in the previous report were observed in 1974 in both the epilimnion and hypolimnion at the six locations surveyed in the eastern portion of the harbour and canal. Periodicities related to lake and harbour oscillations, semi-diurnal processes and the harbour oscillations related to the small canal connection to the lake (so-called Helmholtz modes) were identified in the water chemistry and movement records. These periodicities ranged from 12 hours to 20 minutes and influenced the interpretation of the water quality data obtained by conventional boat survey techniques.

The 1974 report indicated the importance of the exchange process between the harbour and the lake in maintaining water quality in the harbour. Analysis of the data collected in 1974 in the Burlington Ship Canal indicated that mass exchanges of the order of one percent of the harbour volume can occur in one day and persist for periods in excess of 20 days. This is a very large exchange rate compared to the throughput computation based on water balance which indicated an exchange rate of only 80 percent of the harbour volume in one year (mean value of 0.2 percent of the harbour volume per day). The importance of these exchange mechanisms in maintaining water quality in the harbour is obvious. It is important that any modifications to the existing Burlington Ship Canal or developments on the lake side of the canal be carried out in such a way that water quality be maintained in the harbour. It is desirable that any works in the vicinity of the Burlington Ship canal be preceded by an environmental impact statement which demonstrates that such work will not reduce the exchange mechanisms with the lake.

There is an apparent conflict concerning the importance of the canal exchange mechanism in maintaining water quality in the harbour. The results of the numerical model run in the 1974 report showed that increasing these exchange rates did not significantly improve the harbour water quality. The

increased exchange rate between the harbour and the lake used in the numerical model was approximately 0.03 percent of the harbour volume per day. This value was selected as being equivalent to the total industrial discharges to the harbour. The influence of this small exchange rate increase on the water quality could not be detected with the sensitivity of the numerical model. However, if a value of one percent of the harbour volume per day or 810 m^3/sec was used in the numerical model, pronounced changes would occur in the harbour water quality prediction. Artificially pumping such a large quantity of water is nevertheless not a practical consideration for enhancing harbour water quality.

E. Sediment Dissolved Oxygen Uptake

Low dissolved oxygen levels in the hypolimnion were identified as a major water quality concern and artificial mixing was proposed as a means of increasing dissolved oxygen stocks by natural aeration in the 1974 report. In this report it was estimated that bottom sediments and discharges accounted for approximately two-thirds of the dissolved oxygen deficit during the critical period in August. While dissolved oxygen demand of the principal discharges to the harbour are known, sediment demands were unknown. No measurements of sediment dissolved oxygen demand in Hamilton Harbour were undertaken since the 1972 surveys. An extensive literature survey of the sediment dissolved oxygen uptake was undertaken to determine the best manner of measuring these demands and to permit a better estimate of these demands in Hamilton Harbour. This section discusses different methods for assessing sediment dissolved oxygen demand and recomputes the dissolved oxygen demand of sediments using transposed data and the dissolved oxygen budget. Generally it is observed that in situ measurements of sediment dissolved oxygen uptake must be made before reliable estimates of dissolved oxygen demand can be made. Such measurements are expensive as the variability of both the sediments throughout the harbour and the supply mechanisms must be represented.

An estimate of sediment oxygen uptake in Hamilton Harbour for a period (April 28 - August 19) in 1972 was obtained by using measured results obtained from other studies performed under similar conditions. It was estimated that 3 x 10^6 kg of dissolved oxygen was taken up by the sediments in this period, as compared with an estimated deficit of 1.5x10^6 kg (computed from observed and saturation stocks in August 1972). Of this deficit, 0.5 x 10^6 kg of dissolved oxygen was assumed due to seston decay. Estimated values of dissolved oxygen input to the harbour from the mass exchange throughout the canal for the same period ranged from 0.4 to 4.3 x 10^6 kg, depending

upon conditions of flow and stratification in the canal. The importance of the harbour-lake exchange as an oxygen source is apparent when considering stocks. This suggests that the estimate in the 1974 report that effluent and sediment demand represent approximately two-thirds of the deficit is not unreasonable. In May 1972, daily industrial and municipal biological and chemical oxygen demand loadings to the harbour were three times the estimated sediment oxygen demand value. However, all the discharges are to the surface waters with much of the oxygen demand satisfied by aeration, photosynthesis and lake water. Only a portion of the oxygen demanding discharges are particulate matter which will be deposited in the sediments.

F. Phytoplankton

In 1972, measurements were made of chlorophyll a as an indication of phytoplankton standing crops. A better definition of the phytoplankton community was required to predict the effects of artificial destratification. In 1974, enumerations of phytoplankton were made at six locations on six different occasions. The samples were collected by passing a 32 oz. bottle through the euphotic zone. Each sample was identified to genera and standing crop expressed in areal standard units. Unfortunately, the survey was too limited in extent to determine spatial distribution of phytoplankton. There was a conspicuous lack of blue-green algae (Cyanophyceae) although the pH (7.0-8.0) and moderate alkalinity (80-100 mg/l as $CaCO_3$) would provide an abundance of carbon dioxide to support both green and blue-green algae. Genera associated with organically polluted waters such as Euglena, Phacus, Cryptomonas and Rhodomonas predominated. Production is relatively low compared to the levels in Cootes Paradise (connected to the harbour at the western end). The available nutrients in the harbour are sufficient to support large algal populations. The low production in 1974 is likely a result of the lack of stability in the water column due to natural vertical mixing and/or some unidentified toxicity.

Limited zooplankton data show moderate levels which are unlikely to affect phytoplankton levels. One interesting observation was the absence of Daphnia which is common to most fresh water communities.

G.   Artificial Mixing and Water Quality in Hamilton Harbour

Artificial mixing has been used many times to improve water quality and manage biological productivity in aquatic systems. This section presents a literature survey of artificial

mixing experiments, discusses the results and indicates the expected results in Hamilton Harbour.

The general water quality improvements associated with artificial mixing are:

1. Elimination of taste and odour
2. Improved transparency
3. Larger habitat for aquatic life
4. Increased dissolved oxygen
5. Reduced algae blooms
6. More neutral pH as carbon dioxide is released from hypolimnion
7. Decreased dissolved metal content particularly iron and manganese

The success of artificial destratification is dependent on the establishment of an oxidized microzone at the sediment-water interface.

The main goal of the destratification in Hamilton Harbour is to relieve anoxic conditions in the hypolimnion. If the anoxic condition is the factor limiting the establishment of aquatic life a more extensive and diverse habitat should develop capable of supporting an improved fish community. It is expected that primary production will not increase significantly as it will be limited by turbidity. It is also not expected that algal composition will change to blue-greens as control of pH, alkalinity and free carbon dioxide will not favour their development. General water quality should also improve although it is not possible to predict the extent as the chemical and biological responses to artificial destratification are not known.

SUMMARY

Water Quality

With the exception of the ammonia levels, there was no
general improvement in water quality in the harbour between
1972 and 1974. Dissolved oxygen levels in the hypolimnion
appear to have declined since 1972 indicating the need for
corrective action. The importance of dissolved oxygen
supplied by the exchange between the harbour and lake was
identified by estimation of sediment oxygen uptake, as well
as water chemistry and current measurements. Phytoplankton
densities are generally low for the level of nutrients
available. Limited production could be caused by physical
processes preventing the establishment of a stabilized water
column for extended periods of time. The predominant
species are members of the Chlorophyceae. Peculiarities in
zooplankton composition might be related to low dissolved
oxygen levels.

Sediment Analysis

A statistical technique for relating the heavy metal contents
of sediment was applied to the survey data of 1972. It was
found that heavy metal ratios of the sediments in the
eastern and northeastern portion of the harbour were related
to a similar source, probably the Hamilton sewage treatment
plant effluent. The sediment distribution was related to
the predominant circulation patterns in the harbour.

Artificial Mixing

A compilation of data obtained in other artificial mixing
experiments and comparison with conditions in Hamilton
Harbour indicate that such a procedure should eliminate the
dissolved oxygen deficits in the hypolimnion. None of the
other experiments were conducted on such a large body of
water receiving large industrial discharges. Similarly, it
is not known what effect artificial mixing will have on the
exchange mechanisms between the harbour and lake which in
the past have been important in providing dissolved oxygen
to the harbour stocks.

Plankton surveys indicate that the communities are diverse
enough to support fish provided the vertical habitat can be
extended. Artificial mixing should extend this habitat if
the limitation to present production is not related to some
factor other than low dissolved oxygen levels. It is not
expected that the present phytoplankton species (greens)
will increase greatly in density. Blue-green species dens-
ities will be limited by the disruption of stratification.

RECOMMENDATIONS

Water quality surveys should be conducted in support of the
artificial mixing to determine the effect on plankton
communities and productivity, fish abundance and distri-
bution as well as harbour water quality.

Further sediment analysis should be undertaken to identify
sources of contamination.

Proposed works in the region of the ship canal must be
assessed in terms of their influence on the exchange mechanisms
between the harbour and the lake.

HAMILTON HARBOUR STUDY '74

section A

Water quality update

HAMILTON HARBOUR STUDY

SECTION A

WATER QUALITY UPDATE

SUMMARY

RESULTS OF WATER QUALITY SURVEYS CONDUCTED DURING 1974 IN HAMILTON HARBOUR ARE PRESENTED. FOR MOST PARAMETERS, INSUFFICIENT DATA WERE COLLECTED TO DRAW FIRM CONCLUSIONS.

NUTRIENT DATA INDICATED DECREASES FROM 1972 TO 1974 IN AMMONIA AND TOTAL KJELDAHL NITROGEN, AND AN INCREASE IN NITRATE DURING THE SAME PERIOD.

DISSOLVED OXYGEN DATA COLLECTED BY AUTOMATIC DIGITALLY RECORDING WATER QUALITY METERS INDICATED THAT A SEVERE DISSOLVED OXYGEN DEPLETION PROBLEM CONTINUES TO EXIST WITHIN THE HYPOLIMNION. LARGE VARIATIONS IN DISSOLVED OXYGEN CONTENT, WHICH OCCUR WITHIN HOURS NEAR THE HAMILTON SEWAGE TREATMENT PLANT, INDICATE THE VARIABILITY OF LOADINGS AND DYNAMICS IN THE HARBOUR.

BACTERIAL DATA IN 1974 ARE IN GENERAL NOT SIGNIFICANTLY DIFFERENT FROM RESULTS OBTAINED IN 1970-72.

HAMILTON HARBOUR STUDY

WATER QUALITY UPDATE

To assess the continuing changes in water quality in Hamilton Harbour
and the effects of reduced nutrient loadings, a water quality survey was
conducted in 1974 by the Ontario Ministry of the Environment. Surface
and bottom samples were collected at the six locations indicated in Figure
1. In addition, automatic recording water quality meter records of temp-
erature, dissolved oxygen, pH and conductivity were obtained in June
and July near the Windermere Basin (location M8), at the mouth of the
Ottawa Street slip (location M5), and in the epilimnion and hypolimnion
of an offshore location at the eastern end of the harbour about 1 km south
of the Burlington ship canal (locations M6 and M7). The results of the
latter are discussed more fully in Section D, Hamilton Harbour Periodic-
ities and Mass Exchange.

Unfortunately, the six station set was sampled on only four occasions
during 1974, and only two depths were obtained at each station. As a
result detailed statistical analysis of the data is impossible. Enough
data were collected to provide a rough estimate of continuing trends
in nutrients, dissolved oxygen and microbiology. These will be dis-
cussed briefly in turn.

Nutrients

Harbour-wide means for nutrients and chlorophyll $\underline{a}$ are given in Table 1.
It is apparent that a further large decrease in ammonia nitrogen has occur-
red from 1972 to 1974, with 1974 values being largely within the M.O.E.
public surface water criterion of 0.5 mg/l. Accompanying this is a de-
creased total Kjeldahl nitrogen value. This provides continuing evidence
of the decreased industrial loadings previously stated (M.O.E., 1974), and
particularly the diversion by Stelco of ammonia-bearing wastes to the Hamilton
W.P.C.P. early in 1974. Increased bacterial nitrification may also be important,
as the results indicate an increase in nitrate from 1972 to 1974. The 1974
figures are consistent with the previously demonstrated occurrence of nitrifi-
cation during early summer followed by nitrate reduction (M.O.E., 1974),
but no definite conclusion can be drawn from the small data set.

Total phosphorus did not change significantly from 1972 to 1974. An apparent decrease in soluble phosphorus is evident, except possibly in Ocotober. However, the samples for soluble phosphorus were not frozen in the field, as is desirable for proper preservation. Uptake of dissolved phosphorus by microplankton, or adsorption by particulate matter, could have occurred between sampling and analysis. IJC studies indicated that confidence limits were about 0.003 mg/l, comparable to the July-August 1974 means. This is comparable to deviations recorded here.

The July and October chlorophyll a results are considerably lower in 1974 than in 1972. It is difficult to draw a conclusion regarding this parameter, as its seasonal variation is known to be large (individual weekly means in July-October 1972 varied from 11 to 28 ug/l), and a period of high phyto-plankton growth may easily have occurred at some other date in 1974.

Presently secondary treatment is reducing effluent total phosphorus levels from the Hamilton water pollution control plant to less than 1.5 mg/l total phosphorus. By the end of 1975 the plant will be meeting provincial objectives of 1 mg/l.

During 1975, weekly sampling at 4 stations and monthly sampling at 8 stations is to be done to further confirm the existence of seasonal and year-to-year trends.

Dissolved Oxygen

Dissolved oxygen was measured at the six station grid on only two dates in 1974. Values obtained are compared with 1972 data in Table 2. Although no firm conclusion can be drawn from such meager data, they suggest that the DO depletion in 1974 was as great as, if not greater than, that observed in 1972.

Definite evidence of the magnitude of the oxygen depletion problem in 1974 was provided by the results of the automatic digitally-recording water chem-istry meters deployed in June to July at locations M6, M7 and M8. Daily means and standard deviations of temperature, dissolved oxygen, pH and conductivity are indicated in Tables 3 to 5, and a portion of the record obtained in the off-shore location hypolimnion (M7) is shown in Figure 2. That stratification existed during the study is evidenced by the temperature means in Tables 3 and 4, as well as the temperature profile recorded on July 16, 1974 at 1215 hrs. (Figure 3). In the hypolimnion, all daily mean dissolved oxygen values were below 2.5 mg/l, with the minimum daily value recorded on July 13, when the mean was 0.63 mg/l and the maximum reached 0.96 mg/l. This indicates that the hypolimnion of Hamilton Harbour was seriously depleted of oxygen during the entire recorded period. It is hoped that the proposed mixing program in 1975 will alleviate most of this depletion.

A-2

The extent of DO depletion at station 20 as recorded in 1972 varied tremend-ously between successive weekly surveys. Surface values in the July to October 1972 period varied from a minimum of 0.6 mg/l on October 24 to a maximum of 9.6 mg/l on August 6. That large between-day variations of dissolved oxygen do occur is confirmed by the data in Table 5, which were checked and calibrated with in situ field calibration checks. This indicates the variable effect of the Hamilton W.P.C.P. discharge, combined with bio-logical mechanisms of photosynthesis, respiration and sediment oxygen demand, and atmospheric reaeration, on the dissolved oxygen on this portion of the harbour. Because of the remote location relative to the proposed location of the aerator, and shallow depth of this area, combined with the effect of the W.P.C.P. outfall, it is not known if the proposed mixing program will have much effect on dissolved oxygen at this location.

Microbiology

The sampling locations are shown in Figure 1, and the bacteriological water quality data for the 1974 surveys of the Ontario Ministry of the Environment appear in Table 6 (Total Coliform), Table 7 (Fecal Coliform) and Table 8 (Enterococci).

Table 9 indicates the geometric means of fecal coliforms per 100 ml. for the years 1970, 1971, 1972 and 1974. Because of the low number of samples taken in 1974, means are being compared with single samples. The year 1971 still appears as the year with the lowest counts. The significance of the differences between the years was tested statistically with a t-test for some sampling locations with an adequate number of determinations and the results appear in Table 10. The differences between locations are not significantly differ-ent at the 95% significance level; consequently, there are not significant statistical differences between 1970 and 1971, 1971 and 1972, 1972 and 1974, and 1970 and 1974.

By comparison of the related tables of 1972 and 1974, there is an improvement in total coliform and enterococci counts. Fecal coliform counts remained about the same. However, many of the 1974 values are single samples providing at best crude qualitative indicators.

TABLE 1

NUTRIENT SURFACE MEANS, 1972-4

| | JULY | | | | AUGUST | | | | OCTOBER | | | |
| | 1972 | 1974 | | | 1972 | 1974 | | | 1972 | 1974 | | |
	Mean	Mean	S. D.	Number of Samples	Mean	Mean	S. D.	Number of Samples	Mean	Mean	S. D.	Number of Samples
NH_3 (N)	2.4	0.016	0.026	6	1.9	0.30	0.14	5	1.5	0.42	0.35	6
Total Kjeldahl Nitrogen (N)	3.4	2.13	0.78	6	3.0	0.92	0.30	11	2.2	1.30	0.71	6
Nitrate (N)	1.89	2.6	1.8	6	1.77	3.5	0.4	6	1.58	2.5*	0.7	6
Total Phosphorus (P)	0.087	0.067	0.017	6	0.082	0.102	0.048	11	0.093	0.057	0.027	6
Soluble Phosphorus (P)	0.016	0.002	0.002	6	0.024	0.004	0.006	6	0.021	0.017	0.014	6
Chlorophyll a	23	7.8	2.3	6	20	19.3	2.7	6	18	4.6	0.9	6

NOTE: All concentrations are in mg/l, except chlorophyll a in µg/l.

*   This result is $(NO_3 + NO_2) - N$, $NO_2 - N$ results were unreliably high at several points; $NO_3 - N$ is affected as this is obtained by difference.

TABLE 2

DISSOLVED OXYGEN DATA,   1972-74

Date (1974)		Station						Mean D.O.		1972 Mean D.O.	
		20	253	254	256	262	265	mg/l	% Sat.	mg/l	% Sat.
August 21	(surface)	7.5	–	8.7	7.8	7.2	9.8	8.2	96	7.1	84
	(bottom)	3.3	–	0.0	3.0	5.2	4.5	3.2	34	3.7	41
October 2	(surface)	6.2	6.4	6.9	5.7	7.5	–	6.5	62	7.3	77
	(bottom)	5.6	4.4	4.5	7.2	7.2	–	5.8	55	5.4	55

Note: Individual figures are in mg/l. 1972 data are
8 - station means for August 29 and October 4-5.

TABLE 3

WATER QUALTIY METER OPERATED AT OFFSHORE LOCATION EPILIMNION (M6)

DAILY MEANS STARTING AT 16.25 HR ON GIVEN DATE
(HALF - HOURLY READINGS)

DATE		TEMP(C)	D.O.(MG/L)	D.O.(% SATURATION)	PH	COND(25 C)
74192.	MEAN	21.93	6.97	79.14	7.84	527.48
	ST DEV	0.61	1.04	12.61	0.12	7.91
74193.	MEAN	23.18	9.66	112.32	8.27	517.47
	ST DEV	0.57	1.15	14.35	0.20	10.87
74194.	MEAN	23.65	9.58	112.29	8.31	515.40
	ST DEV	0.22	0.80	9.35	0.16	5.66
74195.	MEAN	24.23	7.84	92.94	7.75	521.33
	ST DEV	0.86	0.69	9.09	0.40	4.42
74196.	MEAN	22.18	6.96	79.35	7.88	518.42
	ST DEV	0.46	0.58	6.81	0.19	10.71
74197.	MEAN	21.45	6.37	71.93	7.81	520.52
	ST DEV	0.84	2.14	24.97	0.29	5.58
74198.	MEAN	22.47	8.09	92.68	7.95	517.65
	ST DEV	0.13	1.11	12.63	0.26	5.00
74199.	MEAN	22.55	7.57	86.92	7.86	517.35
	ST DEV	0.22	0.33	3.87	0.15	4.38
74200.	MEAN	21.98	7.11	80.69	7.67	518.40
	ST DEV	0.55	0.65	7.32	0.28	9.39
74201.	MEAN	20.51	6.16	68.03	7.69	511.18
	ST DEV	0.54	0.88	10.36	0.21	9.74
	GRAND MEAN	22.47	7.68	88.26	7.91	518.76
	ST DEV	1.14	1.54	18.87	0.32	8.36

Note: Above dates are stated in terms of 365-day year. Day 74192 is
      July 11, 1974, etc.

TABLE 4

WATER QUALTIY METER OPERATED AT OFFSHORE LOCATION EPILIMNION (M7)

DAILY MEANS STARTING AT 16.25 HR ON GIVEN DATE
(HALF - HOURLY READINGS)

DATE		TEMP(C)	D.O.(MG/L)	D.O.(% SATURATION)	PH	COND(25 C)
74192.	MEAN	12.87	0.86	8.08	7.43	471.23
	ST DEV	0.54	0.49	4.54	0.10	9.33
74193.	MEAN	12.82	0.67	6.35	7.41	471.31
	ST DEV	0.30	0.35	3.24	0.09	7.18
74194.	MEAN	12.99	0.63	5.91	7.40	475.94
	ST DEV	0.23	0.42	3.95	0.10	5.38
74195.	MEAN	12.55	2.00	18.63	7.45	461.19
	ST DEV	0.64	1.09	10.01	0.11	11.88
74196.	MEAN	12.35	1.17	10.87	7.45	460.13
	ST DEV	0.34	0.79	7.28	0.11	7.18
74197.	MEAN	12.50	1.27	11.81	7.45	457.79
	ST DEV	0.48	0.72	6.65	0.11	6.18
74198.	MEAN	12.17	1.21	11.25	7.41	454.50
	ST DEV	0.36	0.63	5.80	0.11	6.70
74199.	MEAN	12.84	1.02	9.56	7.43	463.06
	ST DEV	1.11	0.55	5.07	0.11	14.19
74200.	MEAN	12.52	1.56	14.61	7.44	450.94
	ST DEV	0.51	0.71	6.57	0.10	8.40
74201.	MEAN	12.84	3.01	28.43	7.51	447.19
	ST DEV	0.47	1.09	10.41	0.11	5.72
	GRAND MEAN	12.64	1.28	12.02	7.44	461.81
	ST DEV	0.61	0.93	8.72	0.11	12.09

Note: Above dates are stated in terms of 365-day year. Day 74192 is July 11, 1974, etc.

TABLE 5

WATER QUALITY METER OPERATED NEAR WINDERMERE BASIN (M8)

DAILY MEANS STARTING AT 18.11 HR ON GIVEN DATE
(10 - MINUTE READINGS)

DATE		TEMP(C)	D.O.(MG/L)	D.O.(% SATURATION)	PH	COND(25 C)
74176.	MEAN	18.58	2.49	26.37	0.0	575.65
	ST DEV	0.55	0.83	8.87	0.0	19.69
74177.	MEAN	18.88	2.79	29.67	0.0	581.33
	ST DEV	0.46	1.07	11.44	0.0	13.45
74178.	MEAN	19.17	2.88	31.01	0.0	591.62
	ST DEV	0.41	1.58	17.24	0.0	13.31
74179.	MEAN	19.50	2.51	27.14	0.0	601.77
	ST DEV	0.42	1.17	12.79	0.0	16.53
74180.	MEAN	21.10	7.23	80.23	0.0	608.08
	ST DEV	0.25	0.84	9.43	0.0	34.43
74181.	MEAN	21.32	6.41	71.58	0.0	654.80
	ST DEV	0.42	0.94	10.64	0.0	38.99
74182.	MEAN	22.02	6.09	69.17	0.0	601.58
	ST DEV	0.25	1.01	11.51	0.0	10.70
74183.	MEAN	21.83	6.10	69.30	0.0	604.34
	ST DEV	0.19	1.01	11.58	0.0	17.87
74184.	MEAN	21.09	4.05	44.90	0.0	586.44
	ST DEV	0.37	0.69	7.71	0.0	25.68
74185.	MEAN	22.02	4.61	52.29	0.0	583.10
	ST DEV	0.59	0.64	7.61	0.0	26.40
74186.	MEAN	22.02	3.16	36.09	0.0	584.44
	ST DEV	1.04	1.64	19.04	0.0	20.08
74187.	MEAN	20.85	2.23	25.10	0.0	543.81
	ST DEV	1.26	1.38	15.94	0.0	22.02
74188.	MEAN	23.16	4.88	56.97	0.0	663.89
	ST DEV	0.41	0.73	9.28	0.0	56.27
	GRAND MEAN	20.83	4.25	47.52	0.0	597.71
	ST DEV	1.49	2.01	23.02	0.0	39.06

Note: Above dates are stated in terms of 365-day year. Day 74176 is June 25, 1974, etc.

Meter was not equipped with pH sensor.

TABLE 6:   Hamilton Harbour Survey 1974   Total Coliform/100 ml.

Station Number	Depth in Meters From Surface				
	1.5	10	13	16	19
20	240	775(2)			
253	190(2)	446(2)			
254					192(2)
256				580	
262	1470	1800			
265			1689(2)		

When more than one sample was taken at any location, the geometric mean is reported and the number of samples is recorded in parenthesis.

TABLE 7:   Hamilton Harbour Survey 1974   Fecal Coliform /100 ml

Station Number	Depth in Meters From Surface			
	1.5	10	13	19
20	260	243 (2)		
253	63 (2)	48		
254	114 (2)	452		70 (2)
256	500			
262	364			
265	18 (2)		121 (2)	

When more than one sample was taken at any location, the geometric mean is reported and the number of samples is recorded in paranthesis.

TABLE 8:   Hamilton Harbour Survey 1974   Enterococci/100 ml

Station Number	Depth in Meters From Surface				
	1.5	10	13	16	19
20	29(2)	9(2)			
253	1(2)	4(2)			
254	1(3)				2(3)
256	16(2)		12	27(2)	
262	20(3)	76(3)			
265	1(2)		61(2)		

When more than one sample was taken at any location, the geometric mean is reported and the number of samples is recorded in parenthesis.

TABLE 9

Hamilton Harbour Survey   Geometrical Means of Fecal Coliforms/100 ml.

Station Number	Year 1970	Year 1971	Year 1972	Year 1974
20	831 (8)	246 (5)	319 (14)	260 (1)
256	1026 (7)	359 (5)	488 (14)	500 (1)
262	355 (8)	286 (5)	494 (15)	364 (1)
265	51 (8)	12 (5)	91 (14)	18 (2)

In parenthesis are the number of samples used for calculation of the mean. 1970 and 1971 data are from water pollution surveys of Hamilton Municipal Laboratories. 1972 and 1974 data are from Ministry of Environment surveys at a depth of 1.5 m.

TABLE 10
Hamilton Harbour Survey   t-Test of Fecal Coliforms/100 ml. for 1970-74

Comparison Between Means for Years

Station Number	1970-71		1971-72		1972-74		1970-74	
	D.F.	t	D.F.	t	D.F.	t	D.F.	t
20	11	0.919	17	1.461	–	–		
256	10	0.738	17	1.408	–			
262	11	1.118	17	1.036	–			
265	11	0.948	13	1.200	14	0.651	13	0.6911
(256+20)					38	0.656	24	0.5308
(262+265)					30	1.007	27	0.5776
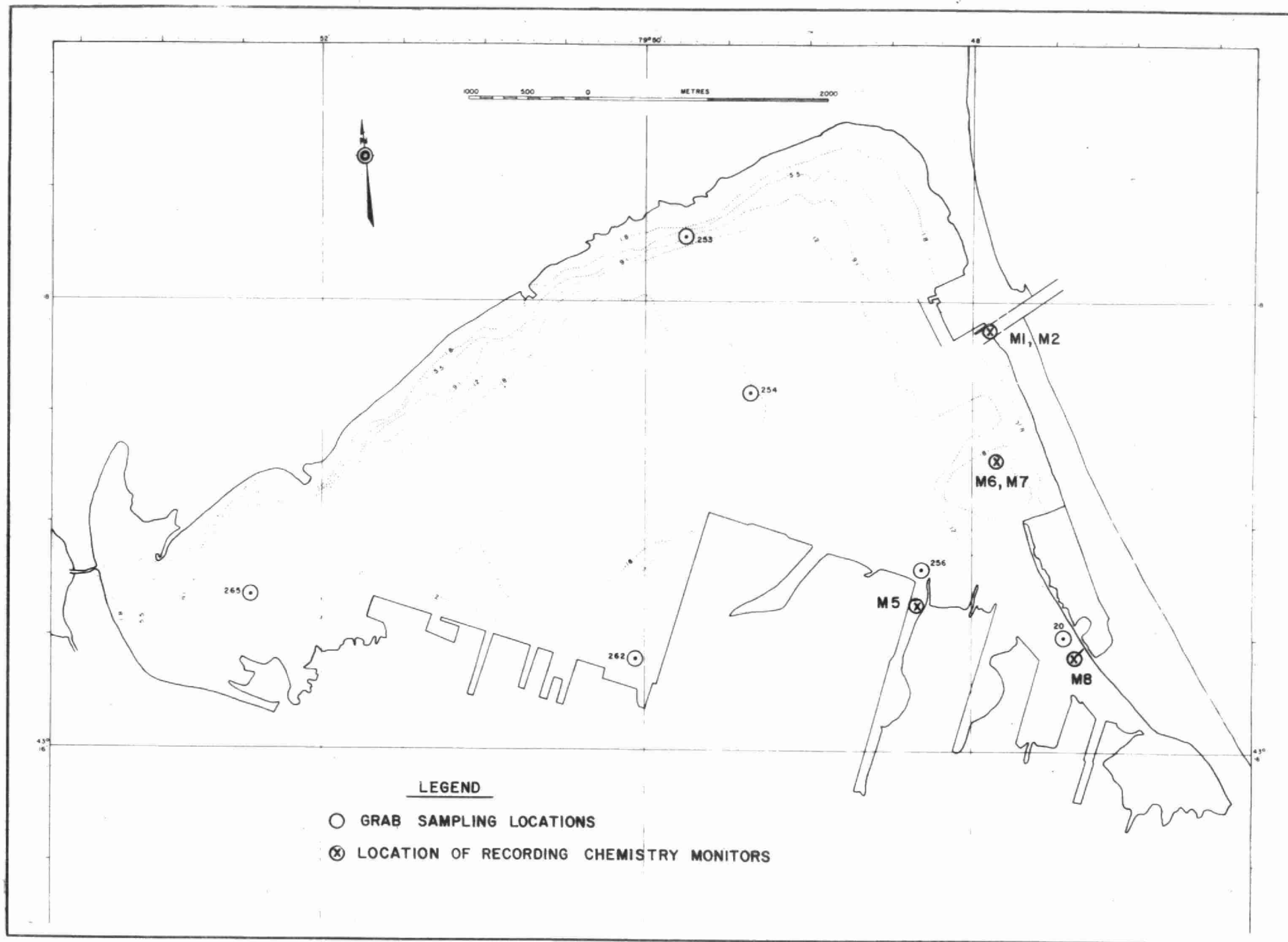
FIG.1 1974 SAMPLING LOCATIONS.

FIGURE 2

DISSOLVED OXYGEN RESULTS
OFFSHORE LOCATION HYPOLIMNION

A-15
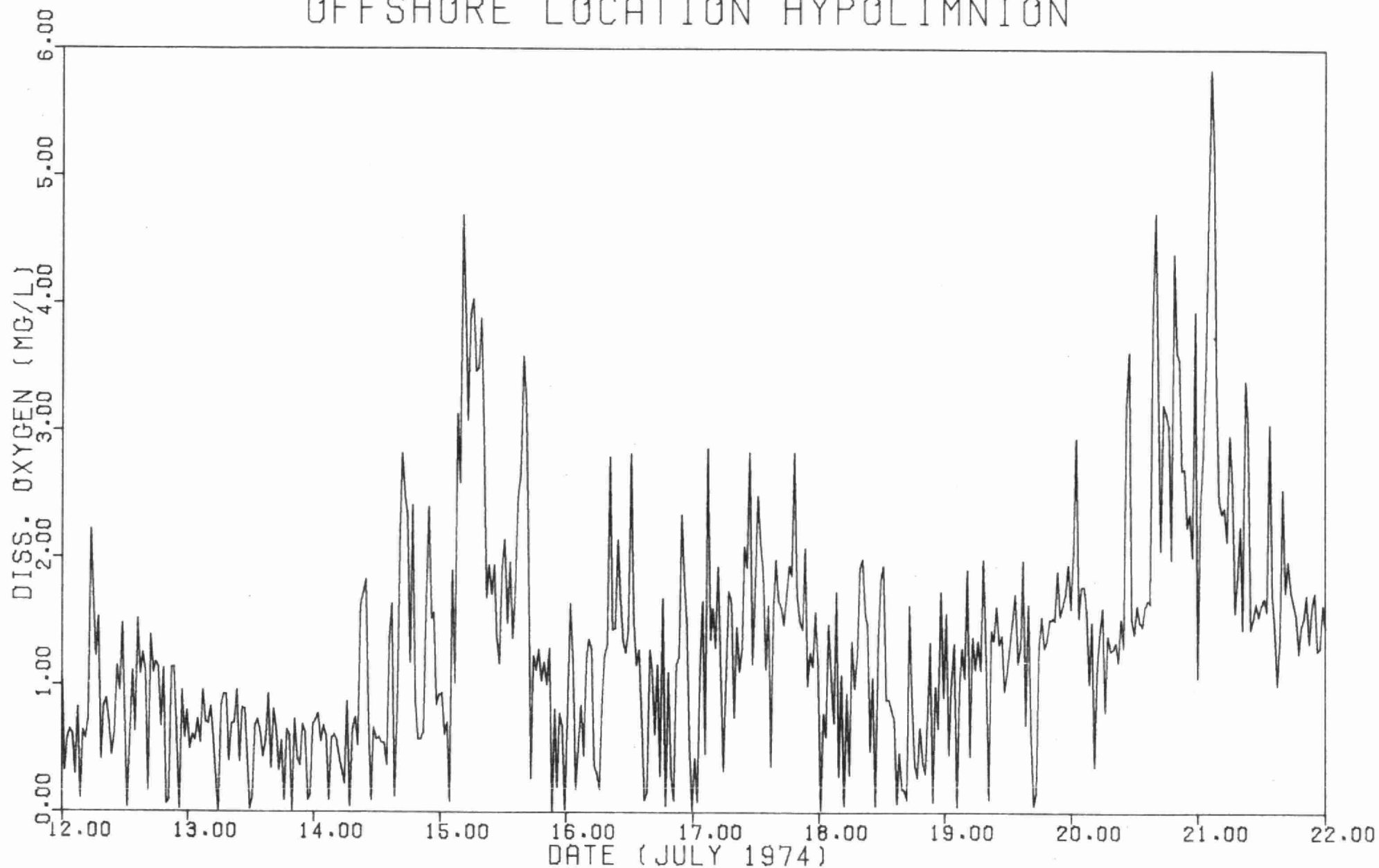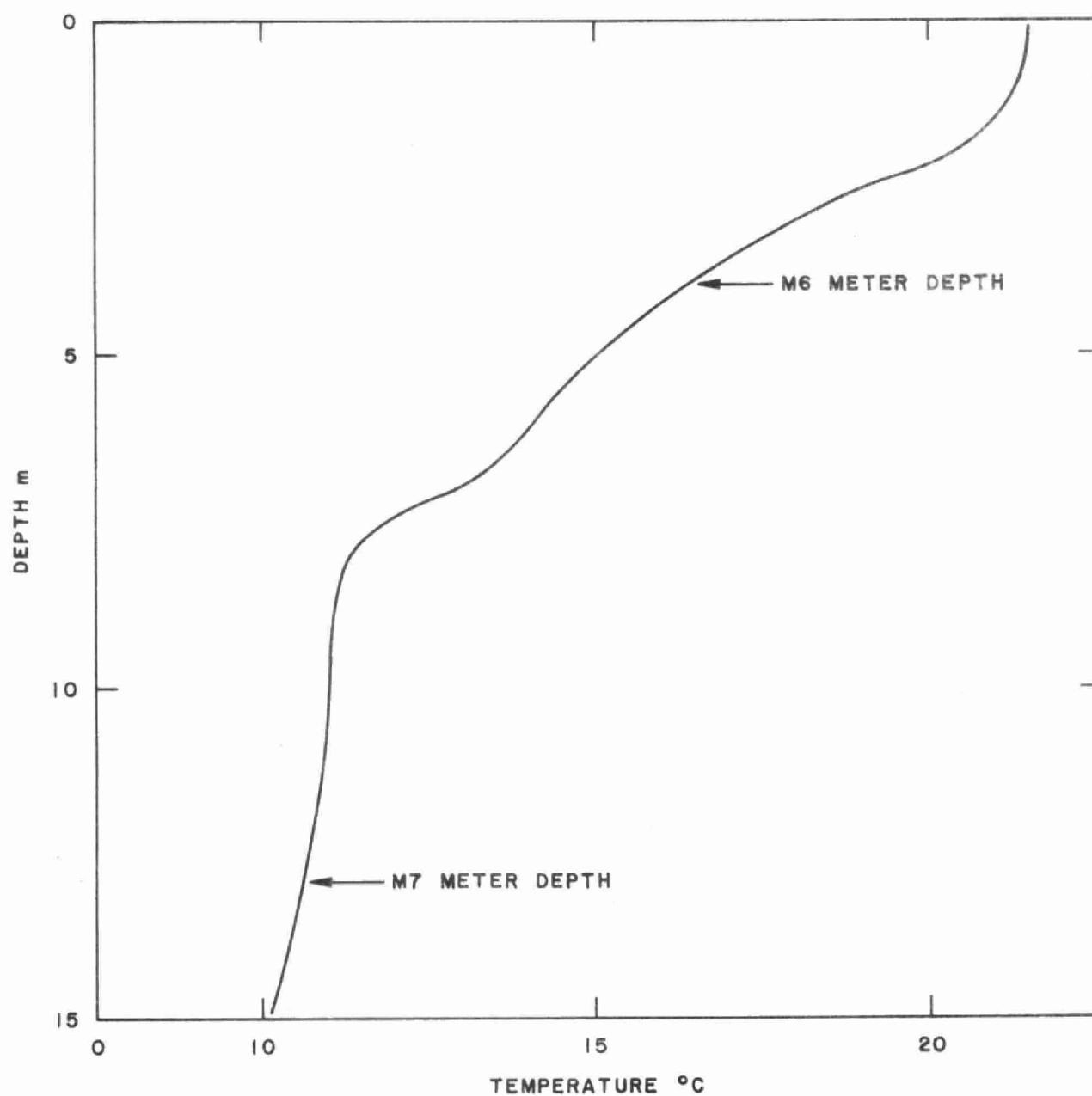
FIG. 3 — TEMPERATURE PROFILE AT OFFSHORE WATER QUALITY
MONITORING SITE, (M6 AND M7)
JULY 16, 1974 AT 12.15 HR.

HAMILTON HARBOUR STUDY '74

section B

Sediment statistical analysis

HAMILTON HARBOUR STUDY

SECTION B

SEDIMENT STATISTICAL ANALYSIS

SUMMARY

THE RELATIONSHIP BETWEEN SEDIMENT SAMPLES HAS BEEN
STATISTICALLY ANALYZED BY COMPARING THE RATIOS OF
CONCENTRATIONS OF TRACE POLLUTANTS. THE SENSITIVITY
OF THE TEST WAS ESTABLISHED BY TESTING RANDOM NUMBERS
FROM LOG-NORMAL AND UNIFORM DISTRIBUTIONS, AND THE
METHOD WAS APPLIED TO 1972 HAMILTON HARBOUR SEDIMENT
DATA. ALTHOUGH THE 1973 DATA WERE INADEQUATE TO
PRESENT CLEARLY DEFINED RELATIONSHIPS, THEY SUGGEST
SIMILAR ORIGINS FOR THE SEDIMENTS ALONG THE EASTERN
AND NORTHEASTERN EDGES OF THE HARBOUR, IN AGREEMENT
WITH OSCILLATORY CURRENTS IN THIS AREA PREDICTED BY
THE NUMERICAL MODEL.

Correlation of Hamilton Harbour Sediment Analyses

In July 1972, as part of the Hamilton Harbour Study, a series of bottom sediment samples was collected and analyzed for PCB, lead, chromium, cadmium, mercury and iron. In the initial discussion of these samples (MOE, 1974), it was stated that high concentrations of heavy metals occurred, with the worst locations near station 262 and the Hamilton WPCP outfall (Station 268). It was further recommended that the sources of heavy metal discharges be identified and some action be taken to reduce these loadings.

To this end, a statistical technique called "ratio matching" (Anders, unpublished) has been modified and adapted for establishing potential generic relationships. This technique is based on the fact that sediment samples of common origin will tend to have similar ratios of concentrations of trace pollutants (heavy metals, PCB, etc.) whereas the absolute concentrations of these individual pollutants may vary considerably due to dilution with inert materials such as SiO_2 and $CaCO_3$. This technique could also be used for developing generic relationships between individuals such as biological communities based on species populations.

For each sample, Anders divides the concentration of each chemical parameter by that of each other parameter to obtain the "concentration ratio matrix", $\{X_{ij}\}$, which is a triangular matrix of size $m \times m$, where m is the number of chemical parameters involved. Two samples A and B are compared by means of the ratio matrix $\{Y_{ij}(AB)\}$, which is generated by dividing each element of the $\{X_{ij}\}_A$ matrix by the corresponding element of the $\{X_{ij}\}_B$ matrix. The ratio matrix of A and B is thus:

$$\{Y_{ij}(AB)\} = \begin{bmatrix} \dfrac{X_{11}(A)}{X_{11}(B)} & & & \\[2em] \dfrac{X_{21}(A)}{X_{21}(B)} & \dfrac{X_{22}(A)}{X_{22}(B)} & & \\[2em] \dfrac{X_{31}(A)}{X_{31}(B)} & \dfrac{X_{32}(A)}{X_{32}(B)} & --- & \\ \vdots & \vdots & & \\ \dfrac{X_{m1}(A)}{X_{m1}(B)} & \dfrac{X_{m2}(A)}{X_{m2}(B)} & ---------- & \dfrac{X_{mm}(A)}{X_{mm}(B)} \end{bmatrix}$$

Here, each X_{ij} represents an element of an $\{X_{ij}\}$ matrix, and there are $\binom{n}{2}$ Y matrices, where n is the number of samples involved.

If two sediment samples have similar origin, then the ratios of the pollutant concentrations of interest will have similar values, and thus the Y_{ij} values will be close to 1. Consequently, Anders proposed that the similarity of each pair of samples be estimated by calculating the proportion of the matrix elements $Y_{ij}(k\ell)$ which satisfy the conditions

$$\frac{1}{M} \leq Y_{ij}(k\ell) \leq M$$

where M is a variable parameter which he called the "matching criterion." Using this condition, each Y matrix produced a quantity called the similarity coefficient.

These similarity coefficients $Z_{k\ell}$ form a "correlation matrix" of size n x n, as follows:

$$\{Z_{k\ell}\} = \begin{bmatrix} 1 & & & & \\ Z_{AB} & 1 & & & \\ Z_{AC} & Z_{BC} & 1 & & \\ \vdots & \vdots & & & \\ Z_{An} & Z_{Bn} & \text{-------} & & 1 \end{bmatrix}$$

Anders suggested that the matching criterion M be chosen such that about 10% of the coefficients from random samples would exceed 0.33. Certainly the value of the method is limited by the need to choose a realistic value for M. If the difference of M from 1 was too large or too small, the statistical resolution of the procedure was seriously limited.

Anders established the statistical significance of a given similarity coefficient by analyzing sets of randomly selected sediment samples from Michigan and California, using values of M = 1.5 and 1.3. He thus obtains a probability of obtaining a given similarity coefficient with random data as a function of the similarity coefficient and of M. However, the nature of the samples used to obtain such a probability is subject to question; he observes higher probabilities of random coefficients when analyzing only Michigan samples as compared to that obtained with both Michigan and California samples. The difference is attributed, reasonably enough, to a geological similarity of the sample sites in Michigan.

Consequently, Anders' procedure bears two shortcomings:
(a) the choice of M, and (b) the choice of "random" samples.
As a result, one is really determining qualitatively which co-
efficients, if any, are significant.

In the past the main difficulty in the analysis of sediment data
was the fact that the concentrations of the chemical parameters
of interest could not be directly employed. Anders has overcome
this problem by implementing the Y concentration ratio matrix
for two samples. Lastly he has offered valuable insight towards
a means of establishing a similarity coefficient from the Y matrix.

In an effort to overcome the difficulties listed above, an alter-
nate method for analyzing the Y matrix has been devised, and is
presented here.

The similarity coefficient is redefined as an evaluation of the
relative differences of all $\{Y_{ij}\}$ $(k\ell)$ matrix elements from 1.
For each of the $\binom{m}{2}$ off-diagonal elements in the $\{Y_{ij}\}$ $(k\ell)$ matrix,
the absolute value of the logarithm is used as a measure of the
difference of the element from 1. As the similarity is inversely
related to the difference of each element from 1, and a value of
1.0 is desired for a perfect correlation (all $\{Y_{ij}\}$ values = 1.0),
1.0 is added to the logarithms, and the similarity coefficient
takes the form

$$Z_{k\ell} = \sum_{i=i}^{m} \sum_{j=i+1}^{m} \left[\frac{1}{\ell n \quad \{Y_{ij}\} \quad (k\ell) \quad + 1} \right] \frac{1}{\binom{m}{2}}$$

In this equation, k and ℓ vary from 2 to n, where n is the
number of samples, $Z_{kk} = 1$ and $Z_{k\ell} = Z_{\ell k}$. Thus a triangular matrix
of size n x n, similar in form to Anders' Z matrix, is obtained.

As previously discussed, the other problem in Anders' method is
the selection of random samples in order to define a statistical
significance for given similarity coefficients. We have used a
random number generator to produce random data from which similarity
coefficients have been calculated and statistically analyzed. The
nature of the distribution from which random data was generated,
the number of "stations" and the number of "chemical parameters"
were all varied. Following this, sediment data provided by Anders
was analyzed to provide a comparison with his method, and the 1972
Hamilton Harbour results are also presented.

RESULTS

The results of several sets of random data analyses are presented
in Table 1. In the first attempts to generate random similarity

coefficients, normal distributions with relatively small standard deviations (10-20% of mean) were used. However, the samples were so similar to each other that all similarity coefficients were significant; indeed, the means of the coefficients were greater than those observed with real data. A better distribution of similarity coefficients was obtained with two other distributions: a log-normal distribution with the natural log of the mean and standard deviations each equal to 1, and a uniform distribution with values between 0 and 100 ppm for each parameter. With either of these distributions, the mean similarity coefficient varied between 0.45 and 0.54, independent of the number of stations or the number of parameters. However, the standard deviations increased from about 0.07 to about 0.12 as the number of chemical parameters was decreased from 8 to 4, while remaining independent of the number of stations involved. As a measure of statistical significance, it was decided to use the parametric Z test (Mendenhall and Scheaffer, 1973). For testing the hypothesis that $r = \rho o$, the test takes the form

$$ Z = 0.5 \left[\ell n \left(\frac{1+r}{1-r} \right) - \ell n \left(\frac{1+\rho o}{1-\rho o} \right) \right] \sqrt{n-2} $$

In this case we are testing whether any similarity coefficient is different from zero ($\rho o = 0$), where n is the number of chemical parameters involved. Although the original formula of Mendenhall and Scheaffer contained $\sqrt{n-3}$ as a multiplier, $\sqrt{n-2}$ was selected here as it produces a better fit with random data over a range of values for n. If $Z > Z\alpha/2$, where α is the significance level selected, the similarity coefficient is indicative of a significant relationship between the two sampling stations involved.

From Table 1, it is seen that the highest similarity coefficients observed in the uniform and log-normal distributions represent probabilities of 90-97% for difference from zero with 8 chemical parameters, and 76-96% for 4 parameters. Accordingly, the 95% probability level was selected as a limiting level for statistical significance; this level is exceeded by not more than 3% of the similarity coefficients in any random data matrix constructed from the uniform or log-normal distributions.

Although maximum similarity coefficients tend to decrease with decreasing number of sampling stations, this is merely a function of the decreased similarity coefficient matrix size, because the use of a subset of a given set of samples will merely produce the corresponding subset of similarity coefficients from the original Z matrix; in addition, mean similarity coefficients in Table 1 are generally independent of the number of samples.

As the use of the parametric Z test assumes that the similarity coefficients are normally distributed, this hypothesis was tested using the Kolmogorov Smirnov test (IBM, 1970; Poulton and Palmer, 1973). Typical probabilities, 0.557 for several sets of random

samples, and 0.464 for coefficients derived from Anders' data and
Hamilton Harbour data, strongly support the assumption of normality.

To provide a comparison with Anders' method, his examples were
re-analysed using the method presented here. Anders' sediment
analysis data are presented in Table 2. The resulting similarity
coefficient matrices are given in Tables 3, 5 and 7, and the
probabilities derived from the Z test are given in Tables 4, 6
and 8. For example 1, only one of the two relationships found by
Anders was significant by this method. If the relationship between
the stations (Figure 2) is accurate, this conclusion is reasonable,
as sediment from the river (location 4291) could be carried through
the lake to the exit (4307). The two methods are in agreement for
examples 2 and 3; in the latter, the most significant correlations
are again between the deep water stations. The occurrence of
several less significant correlations (in agreement with Anders)
may be due to geological similarities as these samples were collected
in an area remote from any heavy metal discharges. In this case
Anders said that a somewhat higher significance level for randomness
should be used; however, no statistical validation of this state-
ment was offered.

Results and Discussion of Hamilton Harbour Data

Analysis of sediment samples collected in 1972 are presented in
Table 9. Sampling locations are given in Figure 1. Unfortunately,
not all samples were analyzed for cadmium and mercury; consequently,
the data were analyzed twice, using 4 parameters for all stations,
and using 6 parameters for stations 20, 256, 257, 262 and 269. The
similarity coefficients and Z-test probabilities are given in Tables
10-13. In the case of the comparison for 4 parameters, none of the
similarity coefficients exceeded the 95% limiting level, which is
0.882. The probability associated with stations 20 and 264 was just
below 95% (Table 11). As these stations are at the opposite ends of
the harbour, it is difficult to justify this finding. As station
264 could be associated with solids derived from the Dundas WPCP,
and station 20 with the Hamilton WPCP, a relationship might be ex-
pected, but solids from the Dundas WPCP should be mainly deposited
in Cootes Paradise, (immediately west of Hamilton Harbour) and have
little effect on the bay itself. In addition, solids from the
Hamilton WPCP should affect station 268 more than station 20. The
lack of a significant relationship between these stations suggests
that solids from the Hamilton WPCP are largely deposited within the
Windermere Basin.

In the 6-parameter case (Tables 12-13), the 95% limiting level for
significance is 0.753. This case reveals the existence of signifi-
cant relationships between stations 20 and 269, and between 257 and
269. As the numerical model (MOE, 1974, section E) indicates major
oscillatory current activity along the eastern and northeastern
shore, it is reasonable to expect sediment movement within an arc
extending between stations 20, 269 and 257.

The use of a statistical criterion dependent upon the number of
chemical parameters is thus supported by the Hamilton Harbour results,
as well as by the random number data presented earlier. The result

of the 4 parameter survey indicates the difficulty in analyzing
inadequate data sets. It is concluded that a minimum of 5 or 6
chemical parameters should be analyzed in order to provide a
reasonable basis for determining the relationships between various
points in the harbour. Increasing the number of sampling stations
does not affect the significance of a similarity coefficient com-
paring any two stations; it merely increases the sensitivity of the
analysis by providing more points for intercomparison.

Furthermore, the chemical parameters chosen should all be those
which are known to be discharged to the harbour as compared to
background substances such as SiO_2, Ca or Mg which are naturally
present in large quantities. The use of the latter could be ex-
pected to increase the value of all similarity coefficients (such
as in the random data sets with small relative standard deviation),
effectively destroying the basis for establishing statistical sig-
nificance.

It is possible that the nature of the sediment sample would intro-
duce a variable factor into this method. Significant variations
in metal concentrations may occur for relatively small changes in
sampling position or depth. The effect of this factor on the sen-
sitivity of the technique should be investigated by taking several
samples from points separated by a few meters, and by analyzing
samples taken from different depths of a core.

In 1975, it is recommended that sediment samples be taken from at
least ten locations within the harbour, and possibly at as many as
twenty locations (the 17 location grid used for chemical sampling
in 1972, plus stations 264, 268 and 1030). Sampling should prefer-
ably be done both before and after the proposed mixing program is
undertaken. All samples should be analyzed for at least five of
the six chemical parameters used in 1972, plus organic carbon, COD,
BOD and Kjeldahl nitrogen. The latter four parameters would allow
for the presence of organic discharges, as well as being of predic-
tive value in the oxygen uptake studies currently in progress. (See
Section E, Sediment Dissolved Oxygen Uptake).

Acknowledgement

Many thanks are due to the assistance of Mr. B. Noble, who performed most of the computer programming associated with this study.

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TABLE 1

SIMILARITY COEFFICIENTS CALCULATED FROM
RANDOM DATA SETS

| Characteristic of Data Set | No. of Stn. | No. of Parameters | Similarity Coefficients | | | Probability of difference from Zero for Maximum |
			Mean	Std. Dev.	Max.	
Normal, each parameter had separate mean in range 0-100 ppm.	13	8	0.6606	0.0682	0.8253	0.991
	8	8	0.7065	0.0707	0.8277	0.992
Normal, mean 10 ppm, SD=2 ppm	13	8	0.8709	0.0333	0.9381	0.998
Uniform distribution in range 0-100 ppm	16	8	0.5262	0.0788	0.7222	0.974
	12	8	0.4526	0.0909	0.6594	0.948
	10	8	0.4650	0.0807	0.6818	0.958
	8	8	0.5063	0.0750	0.6765	0.956
	14	6	0.5288	0.0971	0.7332	0.939
	12	6	0.4834	0.0932	0.7586	0.953
	10	6	0.5294	0.0713	0.6998	0.917
	8	6	0.4880	0.0706	0.6508	0.879
	14	4	0.5391	0.1281	0.9042	0.965
	12	4	0.4981	0.1331	0.8696	0.940
	10	4	0.4785	0.1021	0.7372	0.818
	8	4	0.4607	0.1045	0.7132	0.812
Log-normal distribution, ln mean = 1, ln Std. Dev. = 1	16	8	0.4804	0.0585	0.6672	0.952
	12	8	0.4543	0.0523	0.5881	0.902
	10	8	0.4933	0.0602	0.6367	0.935
	8	8	0.4725	0.0607	0.5924	0.905
	14	6	0.4710	0.0834	0.8012	0.972
	12	6	0.4889	0.0824	0.7501	0.948
	10	6	0.4874	0.0810	0.6813	0.904
	8	6	0.5048	0.0570	0.6110	0.845
	14	4	0.4528	0.1225	0.8730	0.943
	12	4	0.4668	0.1123	0.7968	0.877
	10	4	0.5041	0.1207	0.8384	0.914
	8	4	0.4314	0.0900	0.6811	0.760

TABLE 2

DATA ANALYZED BY ANDERS

Example	Sample	As	Sb	Cu	Zn	Au	Cd	Hg	Cr
	4293	3.5	0.2	12	67	.013	.88	.72	24
I	4291	8.3	1.7	298	386	.075	7.8	.86	31
	4307	12	0.75	124	182	.040	4.0	.41	64
	4298	3.9	.263	34.3	72.9	.025	1.26	1.24	15.1
II	4305	7.8	1.4	29	211	.022	2.52	.26	83
	4303	6.4	.497	83.3	267	.012	7.14	.40	50.8
	4399	5.92	.296	7.07	39.8	.0101	.645	.163	17.8
	21	3.75	.053	1.77	10	.00075	.070	.014	3.74
	22	2.62	.12	7.40	34.3	.00122	.27	.009	10.64
	23	6.3	.32	35.0	112.0	.00361	.873	.148	45.50
III	24	6.68	.095	1.83	16.3	.00054	.030	.021	5.01
	25	4.73	.110	13.1	48.5	.00047	.412	.076	14.30
	26	3.50	.041	0.65	5.0	.00005	.030	.008	1.92
	27	7.25	.491	25.9	109.0	.00374	.727	.122	38.90
	28	12.60	.696	52.0	206.	.00600	1.660	.234	71.70
	29	4.70	.016	1.90	11.5	.00600	.100	.009	0.017
	30	2.74	.036	1.83	9.6	.00016	.064	.008	3.30

NOTE: All concentrations are in ppm.

TABLE 3

MATRIX OF SIMILARITY COEFFICIENTS

EACH COEFFICIENT IS BASED ON A SCALE FROM 0 TO 1

	4293	4291	4307
4293	1.0000	0.5141	0.6225
4291		1.0000	0.6971
4307			1.0000

TABLE 4

ANDERS_DATA_-_EXAMPLE_NUMBER_1

MATRIX OF PROBABILITY STATISTICS FOR SIMILARITY COEFFICIENTS

	4293	4291	4307
4293|	1.0000	0.8361	0.9259
4291|		1.0000	0.9652
4307|			1.0000

TABLE 5

MATRIX OF SIMILARITY COEFFICIENTS

EACH COEFFICIENT IS BASED ON A SCALE FROM 0 TO 1

	4298	4305	4303	4399
4298	1.0000	0.5109	0.5292	0.5459
4305		1.0000	0.5645	0.6647
4303			1.0000	0.5255
4399				1.0000

TABLE 6

MATRIX OF PROBABILITY STATISTICS FOR SIMILARITY COEFFICIENTS

	4298	4305	4303	4399
4298	1.0000	0.8328	0.8509	0.8665
4305		1.0000	0.8827	0.9503
4303			1.0000	0.8473
4399				1.0000

TABLE 7
ANDERS DATA - EXAMPLE NUMBER 3

MATRIX OF SIMILARITY COEFFICIENTS

EACH COEFFICIENT IS BASED ON A SCALE FROM 0 TO 1

	21	22	23	24	25	26	27	28	29	30
21	1.0000	0.5962	0.6070	0.6829	0.5629	0.6355	0.6725	0.6182	0.4604	0.7142
22		1.0000	0.6924	0.5167	0.6064	0.4749	0.7411	0.7449	0.3832	0.6296
23			1.0000	0.5317	0.6874	0.5115	0.8102	0.8742	0.4098	0.6463
24				1.0000	0.5059	0.6553	0.5840	0.5487	0.3789	0.6293
25					1.0000	0.5779	0.6594	0.6889	0.4140	0.6338
26						1.0000	0.5419	0.5199	0.3838	0.6453
27							1.0000	0.8616	0.3895	0.6974
28								1.0000	0.4059	0.6914
29									1.0000	0.4581
30										1.0000

TABLE 8

ANDERS_DATA_-_EXAMPLE_NUMBER_3

MATRIX OF PROBABILITY STATISTICS FOR SIMILARITY COEFFICIENTS

	21	22	23	24	25	26	27	28	29	30
21	1.0000	0.9077	0.9154	0.9590	0.8814	0.9340	0.9542	0.9231	0.7773	0.9718
22		1.0000	0.9632	0.8387	0.9150	0.7941	0.9804	0.9815	0.6774	0.9304
23			1.0000	0.8533	0.9611	0.8334	0.9943	0.9991	0.7138	0.9404
24				1.0000	0.8277	0.9454	0.8985	0.8690	0.6713	0.9302
25					1.0000	0.8937	0.9476	0.9617	0.7194	0.9330
26						1.0000	0.8628	0.8419	0.6783	0.9398
27							1.0000	0.9985	0.6863	0.9653
28								1.0000	0.7085	0.9628
29									1.0000	0.7746
30										1.0000

TABLE 9

ANALYSES OF SEDIMENT, HAMILTON HARBOUR
July 19, 1972

Station	264	15	262	257	255	256	269	1030	267	20	268
PCB (ppm)	.80	2.0	3.0	.58	.05	.17	1.3	.22	.26	.66	10.1
Lead (ppm)	100	420	930	170	25	55	140	60	60	80	340
Chromium (ppm)	40	210	150	120	27	47	97	13	41	43	295
Cadmium (ppm)	–	–	18.5	8	–	5.0	6	–	–	5.0	–
Mercury (ppm)	–	–	1.7	.81	–	.21	.7	–	–	.4	–
Iron %	2.8	6.1	9.4	4.4	1.6	3.3	3.8	1.4	2.3	2.4	3.8

TABLE 10

HAMILTON HARBOUR SEDIMENT DATA -- 4 PARAMETERS

MATRIX OF SIMILARITY COEFFICIENTS

EACH COEFFICIENT IS BASED ON A SCALE FROM 0 TO 1

	264	15	262	257	255	256	269	1030	267	20	268
264	1.0000	0.6775	0.7240	0.6148	0.4888	0.5638	0.7800	0.7015	0.6392	0.8745	0.4748
15		1.0000	0.6727	0.6763	0.4607	0.5255	0.7405	0.6100	0.6636	0.7150	0.5173
262			1.0000	0.5769	0.4861	0.5524	0.6209	0.7157	0.5777	0.6676	0.4917
257				1.0000	0.5790	0.6983	0.7301	0.6788	0.8081	0.6554	0.4609
255					1.0000	0.7612	0.4938	0.4706	0.6241	0.5252	0.3817
256						1.0000	0.5451	0.5594	0.7121	0.5624	0.4243
269							1.0000	0.6200	0.6799	0.8401	0.5210
1030								1.0000	0.6421	0.6718	0.4144
267									1.0000	0.7122	0.4357
20										1.0000	0.4807
268											1.0000

TABLE 11

HAMILTON HARBOUR SEDIMENT DATA -- 4 PARAMETERS

MATRIX OF PROBABILITY STATISTICS FOR SIMILARITY COEFFICIENTS

	264	15	262	257	255	256	269	1030	267	20	268
264	1.0000	0.7564	0.8048	0.6892	0.5502	0.6334	0.8607	0.7816	0.7155	0.9441	0.5346
15		1.0000	0.7513	0.7551	0.5190	0.5910	0.8217	0.6839	0.7416	0.7955	0.5820
262			1.0000	0.6477	0.5472	0.6208	0.6958	0.7962	0.6487	0.7459	0.5535
257				1.0000	0.6501	0.7783	0.8111	0.7578	0.8873	0.7329	0.5191
255					1.0000	0.8723	0.5559	0.5300	0.6993	0.5907	0.4303
256						1.0000	0.6127	0.6285	0.7925	0.6319	0.4782
269							1.0000	0.6948	0.7589	0.9159	0.5860
1030								1.0000	0.7186	0.7504	0.4671
267									1.0000	0.7926	0.4910
20										1.0000	0.5412
268											1.0000

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THE PL/1 STEP OF MOESED HAS EXECUTED COMPLETELY
****

TABLE 12

HAMILTON_HARBOUR_SEDIMENT_DATA_--_6_PARAMETERS

MATRIX OF SIMILARITY COEFFICIENTS

EACH COEFFICIENT IS BASED ON A SCALE FROM 0 TO   1

	262	257	256	269	20
262	1.0000	0.6458	0.5648	0.6937	0.7510
257		1.0000	0.6882	0.7905	0.7223
256			1.0000	0.5860	0.6180
269				1.0000	0.8106
20					1.0000

TABLE 13
HAMILTON HARBOUR SEDIMENT DATA -- 6 PARAMETERS

MATRIX OF PROBABILITY STATISTICS FOR SIMILARITY COEFFICIENTS

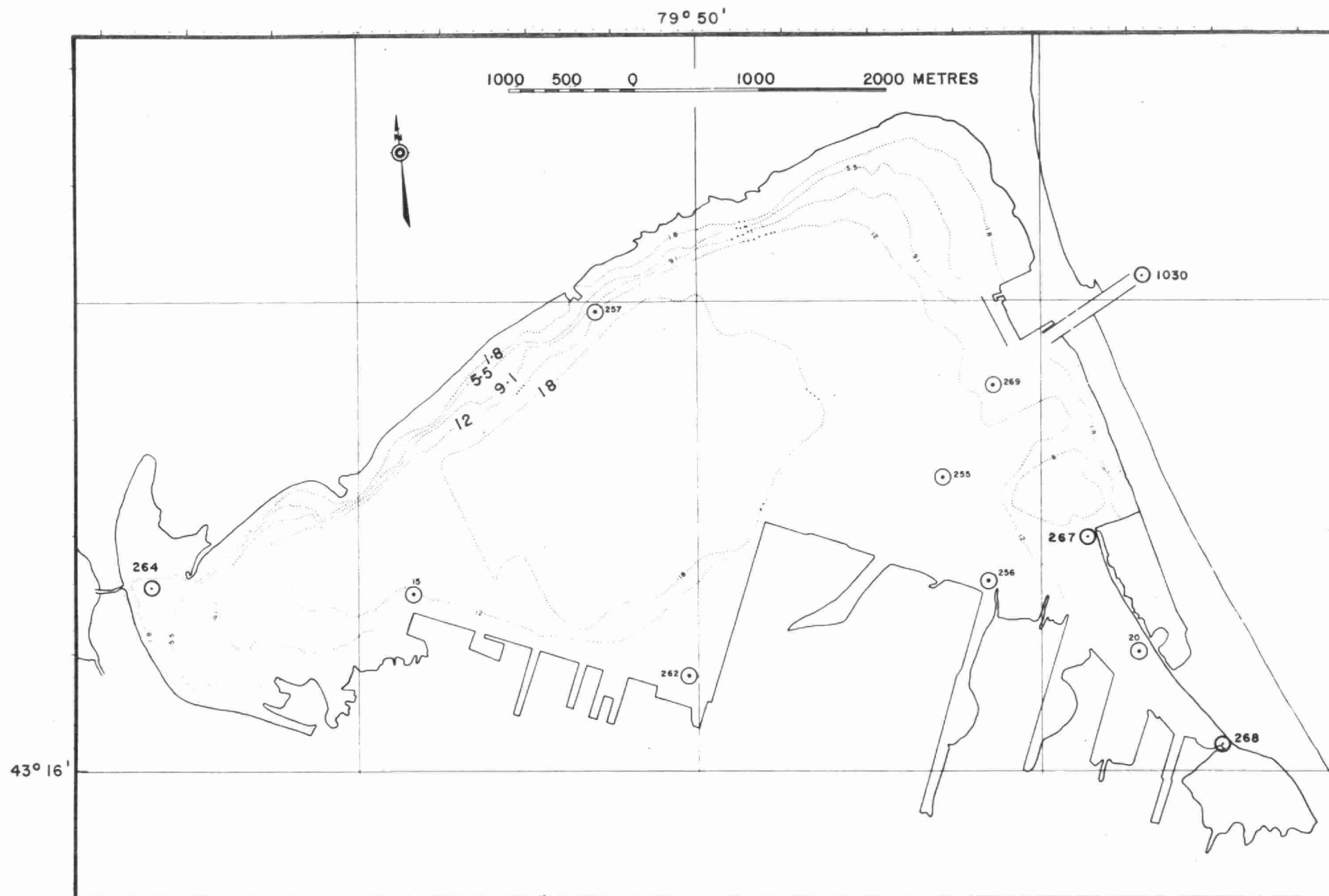|	262	257	256	269	20
262	1.0000	0.8755	0.7993	0.9128	0.9489
257		1.0000	0.9088	0.9681	0.9320
256			1.0000	0.8208	0.8511
269				1.0000	0.9760
20					1.0000

FIGURE: I HAMILTON HARBOUR SEDIMENT SAMPLING LOCATIONS
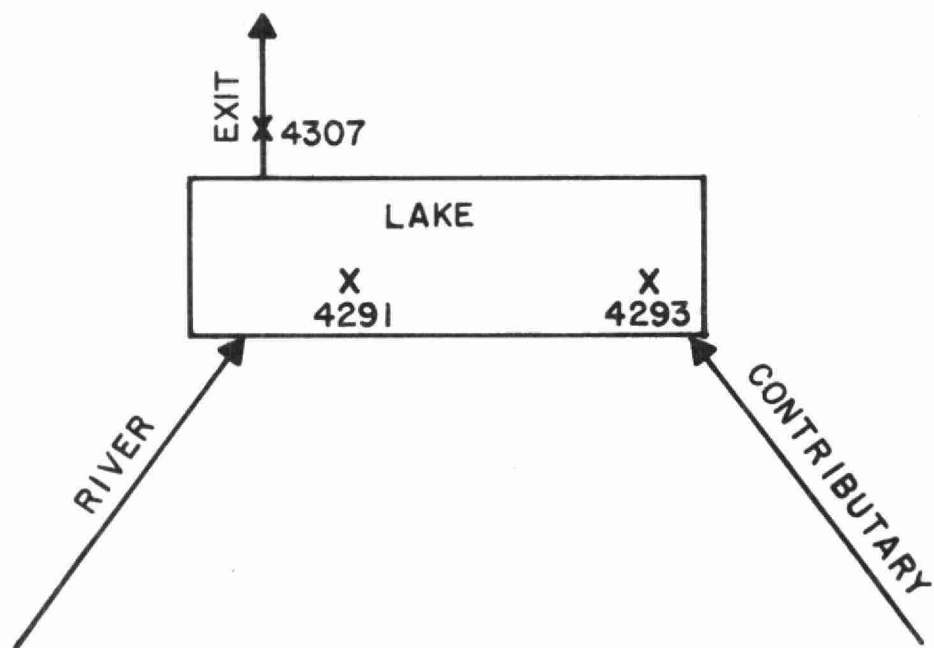JULY 19, 1972

FIG. 2 SITES OF SAMPLES COMPARED IN ANDERS' EXAMPLE I

APPENDIX I - COMPUTER PROGRAM

A program for the evaluation of similarity coefficients has been
developed and is named MOESED. The job consists of two steps,
the first written in PL/1 computes the coefficients, and the
latter is a FORTRAN version of the Kolmogorov-Smirnov Test from
the IBM System/360 Scientific Subroutine Package.

The coefficients generated by the PL/1 step are both printed
out and temporarily stored on disk to be used as input for the
FORTRAN step where they are tested for normality. Matrices of
Z statistics and probability statistics are also printed.

The PL/1 step can accommodate an infinite number of independent
data sets. It is intended that as more and more sediment data
becomes available, their data decks will be added to the program
so that the maximum number of similarity coefficients can be
used in the Kolmogorov-Smirnov Test.

The following pages include a discussion of the program flow and
restrictions, followed by an explanation of the required input
(control cards and data). Finally, the complete source listing
of the PL/1 program is presented.

PROGRAM FLOW

1. Read in title of run

2. Read in: a) indicators as to whether or not to print the computed X and Y matrices.

    b) critical probability value (use a negative number if no particular value is of interest)

    c) number of measuring stations and chemical parameters.

    d) names of chemical parameters and stations.

3. Read in data for one station.

4. Print input data.

5. Compute X matrix.

6. Output X matrix (if indicated).

7. Go back to step 3 until data from all stations are read in.

8. Compute Y matrix from $X_{i...}$ and $X_{i+1...}$.

9. Output Y matrix (if indicated).

10. Go back to step 6 until the Y matrix is formed between the X_n and X_n matrices (n is the subscript of the last X matrix).

11. Compute a matrix of similarity coefficients, store and print.

12. Compute Z test statistic for similarity coefficients derived from Y matrices and print.

13. Compute probability statistic and print. Check for significant probabilities as determined by crit-Z and underscore.

14. Return to step 1 if end of file condition does not exist.

15. Execute step B - Kologmorov-Smirnov Test using the similarity coefficients previously stored on disk.

RESTRICTIONS:

1. The title for each independent data set run is restricted
    to a character string of maximum length 80.

2. The names of the measuring stations are restricted to
    character strings of maximum length 4. Any character on
    the keypunch can be used.

3. The names for the parameters measured are restricted
    to character strings of maximum length 4.

4. The number of stations and parameters measured are limited
    by the core available for execution and secondly the line
    width of the printer. The results are printed out in the
    form of matrices; hence if the line width (132 spaces) is
    exceeded the output will be incomprehensible to one
    unfamiliar with the program. To avoid this the number of
    stations should not exceed 14 and the number of parameters
    should not exceed 12 without altering the output formats.
    Note the size of the arrays are dynamically determined by
    program inputs.

5. There must be an equal number of data items available
    for each station. For example, consider the following
    hypothetical data:-

                 Station A   Station B

              Zn   5 ppm   Zn   3.2 ppm
              Cu   3 ppm   Cu   4.8 ppm
                                     Cd   5.2 ppm

    The above data is insufficient and the program will fail
    unless a measurement for Cd is taken at Station A.

6. The FORTRAN step is limited to 700 similarity coefficients.

                    PROGRAM DOCUMENTATION

    Documentation occurs within the program in the form
    /* comment */. Extra documentation has been included
    for parts which differ from FORTRAN.

INPUT/OUTPUT

STN-NO	number of data measuring stations
PARAM	number of parameters measured at each station
STNS (1:STN-NO)	array of names of stations
PARAMS (1:PARAM)	array of names of attributes
X (1:STN-NO, 1:PARAM, 1:PARAM)	a 3-dimensional array storing the computed concentration ratio matrices for all stations
Y (1:X, 1:PARAM, 1:PARAM)	a 3-dimensional array storing the computed Y ratio matrices of two samples N.B. $X = (num**2-num)/2+num$
INSTRUCT 1, INSTRUCT 2	character strings of a maximum length of 3 for instruction of whether or not to output X and Y matrices respectively.
MASTER	disk file for temporary storage of all similarity coefficients computed
NAME	character string of a maximum length of 80 to label output for each independent run of data sets
COEFF (1:X)	a 1-dimensional array used for similarity coefficients, Z-values and probability statistics
CRIT-Z	critical probability statistic to be used to underscore significant values (N.B. a negative dummy value may be substituted)

CONTROL CARDS

Either the PL/1 F or optimizing compilers can be used. The
optimizing version is preferable because it is more advanced
than its predecessor F. The program is set up to use the
PL/1 F compiler.

The following is the arrangement of the job and the job control
language:

```
// MOESED    JOB (P,0123456,789),'J1R,NAME',CLASS=A

// A EXEC PL1LFCLG,PARM.PLIL='SM=(2,80,1),ATR'

// PL1L.SYSIN DD *

    PL/1  PROGRAM

// GO.MASTER  DD UNIT=DISK,DISP=(,PASS),SPACE=(TRK,(10,11),RLSE)

// GO.SYSIN  DD *

    PL/1 DATA DECK

// B EXEC FORTGCG

// FORT.SYSIN DD *

    FORTRAN PROGRAM

// GO.FT01F001  DD  DSN=*.A.GO.MASTER,DISP=(OLD,DELETE),UNIT=DISK

// GO.SYSIN DD *

//
```

DATA OUTPUT

The output is readily comprehensible providing the restrictions
previously noted are observed.   In the event the restrictions
are deliberately ignored a single row of a given matrix will
appear over two or more lines of printing.   (Also refer to data
input for output options.)

DATA INPUT

Unlike FORTRAN, data input does not require any special format
in PL/1.   For certain inputs, formats may be advantageous,
however, the program SED does not use any.   In light of this,
data can be entered in any position on the card so long as it
is separated from a successive item by either a comma or a blank
or both.

DATA CARDS

DESCRIPTION

1. On the first data card, starting in column 1, enter the
    title of the data set (alphanumeric of maximum length
    80 characters).

2. On the second data card stating in column 1, punch
    --YES-- to print the X matrix (else punch --NO--).
    Leave one blank space and repeat with either --YES--
    or --NO-- for control of printing of the Y matrix.
    Leave one blank space, and then punch a critical P
    value. Note that the critical P value results in heavy
    underscoring of significant probability statistics. A
    dummy negative value may be used.

3. On the third data card enter the number of surveying
    stations, followed by a comma, and then followed by the
    number of parameters examined.

4. On the fourth data card, starting in column 1, enter
    the surveying station names, each name followed by a
    blank space. Note each name must be a string of 4
    characters, thus if the name is less than 4 characters
    add blanks to the end.

5. On the fifth data card, starting in column 1, enter the
    names of the measured parameters, each name followed by
    a blank space. Note each name must be a string of 4
    characters.

6. On the sixth (and additional data cards if required)
    punch in the data, station by station, each number
    followed by a comma.

7. Repeat steps 1 through 6 for another data set.

    NOTE: No data input is required for the FORTRAN step.

```
1               SED:PROCEDURE OPTIONS(MAIN);                                     00000010
                /************************************************************/00000020
                /*                                                          */00000030
                /* MOESED IS A TWO STEP JOB- THE FIRST STEP IN PL/1 CALCULATES THE  */00000040
                /* X AND Y RATIO MATRICES, THE SIMILARITY COEFFICIENT, THE Z TEST   */00000050
                /* VALUE, AND LASTLY THE PROBABILITY OF SIGNIFICANCE.  THE SIMILAR- */00000060
                /* ITY COEFFICIENTS ARE PLACED ON DISK, TO BE USED AS INPUT FOR THE */00000070
                /* FOR THE SECOND STEP- THE IBM SCIENTIFIC SUBROUTINE PACKAGE       */00000080
                /* VERSION OF THE KOLMOGOROV-SMIRNOV TEST ( IN FORTRAN ).           */00000090
                /*                                                          */00000100
                /* THE PROGRAM IS DESIGNED TO HANDLE AS MANY DATA SETS AS AVAILABLE */00000110
                /* TO IMPROVE THE RESULTS OF THE KOLMOGOROV-SMIRNOV TEST, HENCE IT  */00000120
                /* IS ADVISABLE NOT TO REMOVE THE PREVIOUS DATA DECK, BUT INSTEAD   */00000130
                /* TO ADD ON TO IT.  THUS, ONLY THE PL/1 STEP REQUIRES DATA INPUT   */00000140
                /* AND THE FORMAT IS AS FOLLOWS:                             */00000150
                /*                                                          */00000160
                /*      1. ON THE FIRST DATA CARD, STARTING IN COL. 1, ENTER THE    */00000170
                /*         THE TITLE OF THE DATA SET (ALPHANUMERIC OF MAXIMUN LENGTH */00000180
                /*         80 CHARACTERS).                                   */00000190
                /*                                                          */00000200
                /*      2. ON THE SECOND DATA CARD STATING IN COL. 1, PUNCH         */00000210
                /*         --YES-- TO PRINT THE X MATRIX (ELSE PUNCH --NO --).      */00000220
                /*         LEAVE ONE BLANK SPACE AND REPEAT WITH EITHER --YES-- OR  */00000230
                /*         -NO -- FOR CONTROL OF PRINTING OF THE Y MATRIX.  LEAVE ONE*/00000240
                /*         BLANK SPACE, AND THEN PUNCH A CRITICAL PROBABILITY VALUE. */00000250
                /*         NOTE THAT THE CRITICAL Z VALUE RESULTS IN HEAVY UNDER-    */00000260
                /*         SCORING OF SIGNIFICANT PROBABILITY STATISTICS.  A DUMMY   */00000270
                /*         NEGATIVE VALUE MAY BE USED.                       */00000280
                /*                                                          */00000290
                /*      3. ON THE THIRD DATA CARD ENTER THE NUMBER OF SURVEYING     */00000300
                /*         STATIONS, FOLLOWED BY A COMMA, AND THEN FOLLOWED BY THE   */00000310
                /*         NUMBER OF PARAMETERS EXAMINED.                    */00000320
                /*                                                          */00000330
                /*      4. ON THE FOURTH DATA CARD, STARTING IN COL. 1, ENTER THE   */00000340
                /*         SURVEYING STATION NAMES, EACH NAME FOLLOWED BY A BLANK    */00000350
                /*         SPACE.  NOTE EACH NAME MUST BE A STRING OF 4 CHARACTERS,  */00000360
                /*         THUS IF THE NAME IS LESS THAN 4 CHARACTERS ADD BLANKS TO  */00000370
                /*         THE END.                                         */00000380
                /*                                                          */00000390
                /*      5. ON THE FIFTH DATA CARD, STARTING IN COL. 1, ENTER THE    */00000400
                /*         NAMES OF THE MEASURED PARAMETERS, EACH NAME FOLLOWED BY   */00000410
                /*         A BLANK SPACE.  NOTE EACH NAME MUST BE A STRING OF 4      */00000420
                /*         CHARACTERS.                                      */00000430
                /*                                                          */00000440
                /*      6. ON THE SIXTH (AND ADDITIONAL DATA CARDS IF REQUIRED)     */00000450
                /*         PUNCH IN THE DATA, STATION BY STATION, EACH NUMBER FOL-   */00000460
                /*         LOWED BY A COMMA.                                 */00000470
                /*                                                          */00000480
                /************************************************************/00000490
                                                                                 00000500
                                                                                 00000510
```

```
  2   00000520   DECLARE MASTER FILE ENV(VS(3236,404));
  3   00000530   DECLARE STN_NO FIXED,       /* NO. OF MEASURING STNS */
      00000540           PARAM FIXED,        /* NO. OF PARAMETERS/STN */
      00000550           PASSER(1:100) REAL FLOAT, /* FOR RECORDING ON DISK */
      00000560           CODER FIXED,        /* FOR OUTPUT COMMENT */
      00000570           LIMIT FIXED,        /* UPPER BOUND OF COEFF */
      00000580           NAME CHAR(80) VARYING,
      00000590           CRIT_P FLOAT,
      00000600           (INSTRUCT1,INSTRUCT2) CHAR(3) VARYING;
      00000610
      00000620
  4   00000630   ON ENDFILE(SYSIN) GO TO FINAL;
  6   00000640   DO WHILE ('1'B);
      00000650   /* INPUT,CENTER AND PRINT TITLE */
      00000660
  7   00000670   GET FILE(SYSIN) EDIT (NAME)(COL(1),A(80));
  8   00000680   CODER=4;
      00000690
      00000700   /* ASSUME THE NAME OF THE DATA SET ENDS WITH 3 CONSECUTIVE */
      00000710   /* BLANKS.  REMOVE ENDING BLANKS. */
  9   00000720   DO I=1 TO 80 BY 1;
 10   00000730   IF SUBSTR(NAME,I,3)=' ' THEN
 11   00000740   DO;
 12   00000750   NAME=SUBSTR(NAME,1,I-1);
 13   00000760   I=90;
 14   00000770   END;
 15   00000780   END;
 16   00000790   CALL TITLE (NAME,CODER);
 17   00000800   GET FILE(SYSIN) EDIT (INSTRUCT1,INSTRUCT2,CRIT_P)(COL(1),A(2),A(3)
      00000810   ),X(1),E(12,6));
      00000820
      00000830   /* CALCULATE ARRAY STORAGE REQUIREMENTS */
 18   00000840   GET FILE(SYSIN) LIST (STN_NO,PARAM);
 19   00000850   LIMIT=(STN_NO**2-STN_NO)/2EO+STN_NO;
      00000860
      00000870
 20   00000880   DSTORE:BEGIN;
      00000890
 21   00000900   DECLARE STNS(1:STN_NO) CHAR(4) VARYING,  /* STATION NAMES */
      00000910           (F,H) FIXED,        /* INDEXING VARIABLES */
      00000920           PARAMS(1:PARAM) CHAR(4) VARYING, /* PARAM NAMES */
      00000930           X(1:STN_NO,1:PARAM,1:PARAM) FLOAT,
      00000940           Y(1:LIMIT,1:PARAM,1:PARAM) FLOAT,
      00000950           COEFF(1:LIMIT) FLOAT;
      00000960
 22   00000970   F=PARAM*10+5;
      00000980   /* READ IN STATION NAMES */
 23   00000990   GET FILE(SYSIN) EDIT (STNS)(COL(1),(STN_NO)(A(4),X(1)));
      00001000   /* READ IN PARAMETER NAMES */
 24   00001010   GET FILE(SYSIN) EDIT (PARAMS)(COL(1),(PARAM)(A(4),X(1)));
      00001020
      00001030   /* READ IN ALL THE INPUT DATA FOR EACH STATION, ONE STATION */
      00001040   /* AT A TIME, PRINT THE INPUT DATA, COMPUTE THE X CONCEN- */
      00001050   /* TRATION MATRIX, AND IF INSTRUCTED TO, PRINT THIS MATRIX. */
 25   00001060   DO J=1 TO STN_NO BY 1;
 26   00001070   PUT FILE(SYSPRINT) SKIP(5) EDIT ('INPUT DATA FOR STATION',
      00001080   STNS(J))(X(54),A,X(1),A);
```

```
27                              PUT FILE(SYSPRINT) SKIP;                         00001090
28                              DO I=1 TO PARAM BY 1;                            00001100
29                                 GET FILE(SYSIN) LIST (COEFF(I));              00001110
30                                 PUT FILE(SYSPRINT) SKIP EDIT (COEFF(I),' PPM',PARAMS(I))00001120
                                      (X(57),F(9,3),A,X(1),A);                   00001130
31                              END;                                            00001140
32                              DO I=1 TO PARAM BY 1;                            00001150
33                                 DO K=1 TO I BY 1;                            00001160
34                                    X(J,I,K)=COEFF(I)/COEFF(K);              00001170
35                                 END;                                         00001180
36                              END;                                            00001190
37                              IF INSTRUCT1='YES' THEN                          00001200
38                                 DO;                                          00001210
39                                    PUT FILE(SYSPRINT) SKIP(2) EDIT ('COMPUTED ', 00001220
                                         'CONCENTRATION RATIO MATRIX FOR STATION',STNS(J))00001230
                                         (X(1),A,A,X(1),A);                      00001240
40                                    PUT FILE(SYSPRINT) SKIP;                   00001250
41                                    PUT FILE(SYSPRINT) SKIP EDIT  ('|',(PARAMS(I),'|' 00001260
                                         DO I=1 TO PARAM))(X(5),A,(PARAM)(X(3),A,X(2),A 00001270
                                         );                                      00001280
42                                    DO I=1 TO PARAM BY 1;                      00001290
43                                       H=PARAM-I;                             00001300
44                                       PUT FILE(SYSPRINT) SKIP EDIT (('-' DO G=1 TO F)) 00001310
                                            (X(1),(F)A);                         00001320
45                                       PUT FILE(SYSPRINT) SKIP EDIT (PARAMS(I),'|',(X(J,I00001330
                                            ,K),'|' DO K=1 TO I),('|' DO G=1 TO H))(X(1) 00001340
                                            ,A,A,(I)(F(9,4),A),(H)(X(9),A));     00001350
46                                    END;                                      00001360
47                                    PUT FILE(SYSPRINT) SKIP EDIT (('-' DO G=1 TO F)) 00001370
                                         (X(1),(F)A);                            00001380
48                                 END;                                         00001390
49                              END;                                            00001400
                                                                                00001410
                                /* COMPUTE THE CONCENTRATION RATIO MATRIX FOR THE COM-   */00001420
                                /* PARISON OF TWO STATIONS AND IF INSTRUCTED TO, PRINT IT */00001430
50                              LIMIT=0;                                        00001440
51                              DO I=1 TO STN_NO BY 1;                          00001450
52                                 DO J=I TO STN_NO BY 1;                      00001460
53                                    LIMIT=LIMIT+1;                           00001470
54                                    DO K=1 TO PARAM BY 1;                    00001480
55                                       DO L=1 TO K BY 1;                     00001490
56                                          Y(LIMIT,K,L)=X(I,K,L)/X(J,K,L);    00001500
57                                       END;                                   00001510
58                                    END;                                      00001520
59                                    IF INSTRUCT2='YES' THEN                   00001530
60                                       DO;                                    00001540
61                                          PUT FILE(SYSPRINT) SKIP(5) EDIT ('COMPARISON ', 00001550
                                               'RATIO MATRIX FOR STATIONS ',STNS(I),' VS. ', 00001560
                                               STNS(J))(X(1),A,A,A,A,A);        00001570
62                                          PUT FILE(SYSPRINT) SKIP EDIT ('|',(PARAMS(G),'|' 00001580
                                               DO G=1 TO PARAM))(X(5),A,(PARAM)(X(3),A,X(2), 00001590
                                               A));                             00001600
63                                          DO K=1 TO PARAM BY 1;               00001610
64                                             H=PARAM-K;                       00001620
65                                             PUT FILE(SYSPRINT) SKIP EDIT (('-' DO G=1 TO F00001630
                                                  )(X(1),(F)A);                 00001640
66                                             PUT FILE(SYSPRINT) SKIP EDIT (PARAMS(K),'|',( 00001650
```

```
                                            Y(LIMIT,K,L),'|' DO L=1 TO K),('|' DO L=1     00001660
                                            TO H))(X(1),A,A,(K)(F(9,4),A),(H)(X(9),A)     00001670
                                            );                                           00001680
    67                                  END;                                             00001690
    68                              PUT FILE(SYSPRINT) SKIP EDIT (('-' DO G=1 TO F))      00001700
                                        (X(1),(F)A);                                     00001710
    69                          END;                                                     00001720
    70                      END;                                                         00001730
    71                  END;                                                             00001740
                                                                                        00001750
                        /* CALCULATE SIMILARITY COEFFICIENT AND PRINT IT */              00001760
    72                  CALL SIM(Y,COEFF);                                               00001770
    73                  CODER=1;                                                         00001780
    74                  CALL TITLE(NAME,CODER);                                          00001790
    75                  CODER=4;                                                         00001800
    76                  CALL PRINT (COEFF,STNS,CRIT_P,CODER);                            00001810
                        /* CALCULATE Z_TEST VALUE AND PRINT IT */                        00001820
    77                  CALL Z_TEST(COEFF,PARAM);                                        00001830
    78                  CODER=2;                                                         00001840
    79                  CALL TITLE (NAME,CODER);                                         00001850
    80                  CODER=4;                                                         00001860
    81                  CALL PRINT(COEFF,STNS,CRIT_P,CODER);                             00001870
                        /* CALCULATE PROBABILITY STATISTIC AND PRINT IT */               00001880
    82                  CALL P_STAT(COEFF);                                              00001890
    83                  CODER=3;                                                         00001900
    84                  CALL TITLE(NAME,CODER);                                          00001910
    85                  CALL PRINT (COEFF,STNS,CRIT_P,CODER);                            00001920
    86                END DSTORE;                                                        00001930
                                                                                        00001940
    87              END;                                                                00001950
    88              FINAL:DO;                                                           00001960
    89                 PASSER=999999.0;                                                 00001970
    90                 WRITE FILE (MASTER) FROM (PASSER);                               00001980
    91              END;                                                                00001990
```

```
          /*******************************************************************/00002000
          /*                                                                 */00002010
          /*   THE INTERNAL SUBROUTINE TITLE OUTPUTS A TITLE AND A BRIEF COMMENT*/00002020
          /*   AS DEFINED BY THE PARAMETER CODER2.                           */00002030
          /*              CODER2 = 1  -  FOR SIMILARITY COEFFICIENT           */00002040
          /*              CODER2 = 2  -  FOR Z_TEST VALUE                     */00002050
          /*              CODER2 = 3  -  FOR PROBABILITY STATISTIC            */00002060
          /*              CODER2 = 4  -  FOR NO COMMENT                       */00002070
          /*                                                                 */00002080
          /*******************************************************************/00002090
                                                                              00002100
                                                                              00002110
   92     TITLE:PROCEDURE (HEADING,CODER2);                                    00002120
                                                                              00002130
                                                                              00002140
   93        DECLARE HEADING CHAR(80) VARYING,           /* THE TITLE */      00002150
                    CODER2 FIXED,                                             00002160
                    (E,F,G) FIXED,           /* CENTERING VARIABLES */        00002170
                    PLACE(1:4) LABEL INITIAL(PR1,PR2,PR3,PR4);                00002180
                                                                              00002190
   94        F=(132-LENGTH(HEADING))/2E0;                                     00002200
   95        PUT FILE(SYSPRINT) PAGE EDIT (HEADING)(X(E),A);                  00002210
   96        G=LENGTH(HEADING);                                               00002220
   97        PUT FILE(SYSPRINT) SKIP(0) EDIT (('_' DO H=1 TO G))(X(E),(G)A);  00002230
   98        GO TO PLACE(CODER2);                                             00002240
   99        PR1: PUT FILE(SYSPRINT) SKIP(2) EDIT ('MATRIX OF SIMILARITY ',   00002250
                     'COEFFICIENTS')(X(50),A,A);                              00002260
  100            PUT FILE(SYSPRINT) SKIP (2) EDIT ('EACH COEFFICIENT IS BASED ',00002270
                     'ON A SCALE FROM 0 TO 1')(X(42),A,A);                    00002280
  101            RETURN;                                                      00002290
  102        PR2: PUT FILE(SYSPRINT) SKIP (2) EDIT ('MATRIX OF Z_TEST ',      00002300
                     'STATISTICS FOR SIMILARITY COEFFICIENTS')(X(38),A,A);    00002310
  103            RETURN;                                                      00002320
  104        PR3: PUT FILE(SYSPRINT) SKIP (2) EDIT ('MATRIX OF PROBABILITY ', 00002330
                     'STATISTICS FOR SIMILARITY COEFFICIENTS')(X(36),A,A);    00002340
  105            RETURN;                                                      00002350
  106        PR4: RETURN;                                                     00002360
                                                                              00002370
  107     END TITLE;                                                          00002380
```

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```
              /*******************************************************************/00002390
              /*                                                             */00002400
              /*   THE INTERNAL SUBROUTINE PRINT LABELS AND OUTPUTS A TRIANGULAR  */00002410
              /*   MATRIX CENTERED IN A 132 CHARACTER PRINT FIELD. THE PARAMETER  */00002420
              /*   MATRIX IS A ONE DIMENSIONAL ARRAY. IF A MATRIX OF PROBABILITY  */00002430
              /*   STATISTICS IS BEING PRINTED (INDICATED BY SETTING THE PARAMETER */00002440
              /*   CODER1=3) THEN SIGNIFICANT RESULTS WILL BE UNDERSCORED IF A     */00002450
              /*   SIGNIFICANT CRIT_P VALUE IS PASSED.                        */00002460
              /*                                                             */00002470
              /*******************************************************************/00002480
                                                                            00002490
                                                                            00002500
      108         PRINT:PROCEDURE (MATRIX,LOCALE,CRIT_P,CODER1);              00002510
                                                                            00002520
                                                                            00002530
      109            DECLARE MATRIX(*) FLOAT,                                 00002540
                        LOCALE(*) CHAR(4)  VARYING,     /* STATION NAMES */   00002550
                        CODER1 FIXED,                /* TITLE OF MATRIX */    00002560
                        CRIT_P FLOAT,               /* CRITICAL P VALUE */    00002570
                        (SP,JN) FIXED,             /* CENTERING VARIABLES */  00002580
                        (F,G,H,I,I2,J,J2,K,R,S) FIXED (3,0);  /* FOR INDEXING */  00002590
                                                                            00002600
              /* COMPUTE NECESSARY SPACING TO CENTER MATRIX.  NOTE, IF THE SIZE */00002610
              /* OF MATRIX EXCEEDS 12 X 12 THE OUTPUT OF EACH ROW WILL APPEAR   */00002620
              /* ON ONE OR MORE PRINTING LINES.                            */00002630
                                                                            00002640
      110            JN=(132-9*HBOUND(LOCALE,1)-4)/2E0;                       00002650
      111            IF JN<0 THEN JN=0;                                       00002660
      113            PUT FILE(SYSPRINT) SKIP(5) EDIT ('|',(LOCALE(I),'|' DO I=1 TO  0002670
                        HBOUND(LOCALE,1)))(X(JN+4),A,(HBOUND(LOCALE,1))(X(2),A,X(2),A));00002680
      114            K=HBOUND(LOCALE,1);                                      00002690
      115            I=1;                                                     00002700
      116            I2=I;                                                    00002710
      117            F=K*9+5;                                                 00002720
      118            DO J=1 TO HBOUND(LOCALE,1) BY 1;                         00002730
      119              R=K-I+1;                                               00002740
      120              H=HBOUND(LOCALE,1)-R;                                  00002750
      121              PUT FILE(SYSPRINT) SKIP EDIT  (('-' DO G=1 TO F))(X(JN),(F)A); 00002760
      122              PUT FILE(SYSPRINT) SKIP EDIT (LOCALE(J),'|',('|' DO L=1 TO H), 00002770
                        (MATRIX(S),'|' DO S=I TO K))(X(JN),A,A,(H)(X(8),A),(R) 00002780
                        (F(7,4),X(1),A));                                     00002790
      123              IF CRIT_P>0 THEN                                       00002800
      124                IF CODER1=3 THEN                                     00002810
      125                  DO;                                               00002820
      126                    SP=JN+4+H*9;                                    00002830
      127                    DO J2=I2 TO K BY 1;                             00002840
      128                      IF (MATRIX(J2)>=CRIT_P &  MATRIX(J2)<1.0000) THEN 00002850
      129                        DO;                                         00002860
      130                          PUT FILE(SYSPRINT) SKIP(0) EDIT ('_____')(X( 00002870
                                    SP),A);                                  00002880
      131                          PUT FILE(SYSPRINT) SKIP(0) EDIT ('_____')(X( 00002890
                                    SP),A);                                  00002900
      132                          SP=SP+9;                                  00002910
      133                        END;                                        00002920
      134                    END;                                            00002930
      135                  END;                                              00002940
      136              I=K+1;                                                00002950
```

```
                /**********************************************************************/00003020
                /*                                                      */00003030
                /*   THE INTERNAL SUBROUTINE SIM COMPUTES THE SIMILARITY COEFFICIENT, */00003040
                /*   FROM THE PARAMETER Y.  THE MATRIX OF COEFFICIENTS ARE RETURNED    */00003050
                /*   IN THE S_COEFF PARAMETER. IN ADDITION, THE VALUE OF THE COEFF.    */00003060
                /*   IS STORED WITHOUT FORMATTING ONTO DISK FOR USE IN THE FORTRAN     */00003070
                /*   STEP.                                              */00003080
                /*                                                      */00003090
                /**********************************************************************/00003100
                                                                         00003110
                                                                         00003120
142             SIM:PROCEDURE (Y,S_COEFF);                               00003130
                                                                         00003140
                                                                         00003150
143                 DECLARE Y(*,*,*) FLOAT,            /* Y MATRIX */     00003160
                        PASSER(1:100) REAL FLOAT INITIAL (10E0), /* FOR RECORDING */00003170
                        S_COEFF(*) FLOAT,           /* SIMILARITY COEFFICIENT */    00003180
                        CHOOSE FLOAT;               /* N CHOOSE 2 */      00003190
                                                                         00003200
                    /* COMPUTE SIMILARITY COEFFICIENT */                 00003210
144                 S_COEFF=0;                                           00003220
145                 CHOOSE=HBOUND(Y,2);                                  00003230
146                 CHOOSE=1E0/((CHOOSE**2-CHOOSE)/2E0);                 00003240
147                 DO I=1 TO HBOUND(S_COEFF,1) BY 1;                    00003250
148                   DO J=1 TO HBOUND(Y,2) BY 1;                        00003260
149                     DO K=1 TO (J-1) BY 1;                            00003270
150                       S_COEFF(I)=S_COEFF(I)+CHOOSE/(ABS(LOG(Y(I,J,K)))+1E0);00003280
151                     END;                                             00003290
152                   END;                                               00003300
153                 END;                                                 00003310
                    /* RECORD SIMILARITY COEFFICIENT ON DISK */          00003320
154                 J=1;                                                 00003330
155                 K=100;                                               00003340
156                 RECD:DO I=J TO K BY 1 WHILE(I<=HBOUND(S_COEFF,1));    00003350
157                   PASSER(I)=S_COEFF(I);                              00003360
158                 END RECD;                                            00003370
159                 WRITE FILE (MASTER) FROM (PASSER);                   00003380
160                 IF (I<(HBOUND(S_COEFF,1))) THEN                      00003390
161                   DO;                                                00003400
162                     K=I+100;                                         00003410
163                     J=I;                                             00003420
164                     GO TO RECD;                                      00003430
165                   END;                                               00003440
                                                                         00003450
166             END SIM;                                                 00003460
```

```
          /***********************************************************************/00003470
          /*                                                                   */00003480
          /*    THE INTERNAL SUBROUTINE Z_TEST COMPUTES A Z_TEST VALUE FOR THE  */00003490
          /*    NULL HYPOTHESIS: THE SIMILARITY COEFFICIENT=0 (SEE REFERENCE 3, */00003500
          /*    PAGE B11, HAMILTON HARBOUR STUDY).  THE ARRAY OF Z_TEST VALUES  */00003510
          /*    ARE RETURNED IN THE PARAMETER S_COEFF.                          */00003520
          /*                                                                   */00003530
          /***********************************************************************/00003540
                                                                                 00003550
                                                                                 00003560
  167     Z_TEST:PROCEDURE (S_COEFF,NUMBER);                                      00003570
                                                                                 00003580
                                                                                 00003590
  168        DECLARE S_COEFF(*) FLOAT,          /* SIMILARITY COEFFICIENT */     00003600
                     DF FLOAT,                   /* DEGREES OF FREEDOM */         00003610
                     NUMBER FIXED;               /* NO. OF CHEMICAL PARAMETERS */ 00003620
                                                                                 00003630
  169        DF=SQRT(NUMBER-2);                                                   00003640
  170        DO J=1 TO HBOUND(S_COEFF,1) BY 1;                                    00003650
  171           S_COEFF(J)=(0.5E0*LOG((1E0+S_COEFF(J))/(1E0-S_COEFF(J))))*DF;     00003660
  172        END;                                                                 00003670
                                                                                 00003680
  173     END Z_TEST;                                                             00003690
```

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```
      /*************************************************************/00003900
      /*                                                          */00003910
      /*    THE INTERNAL FUNCTION NDTR IS A PL1 TRANSLATION CF THE FORTRAN    */00003920
      /*    SUBROUTINE OF THE SAME NAME, LISTED IN THE IBM SYSTEM/360         */00003930
      /*    SCIENTIFIC SUBROUTINE PACKAGE PUBLICATION.  THE CALCULATED PROB-  */00003940
      /*    ABILITY IS RETURNED TO THE POINT WHERE THE PROCEDURE IS INVOKED.  */00003950
      /*                                                          */00003960
      /*************************************************************/00003970
                                                                   00003980
                                                                   00003990
181           NDTR:PROCEDURE (EX,P);                               00004000
                                                                   00004010
                                                                   00004020
182               DECLARE (EX,DEN,AX,P,T) FLOAT;                   00004030
                                                                   00004040
183               AX=ABS(EX);                                      00004050
184               T=1E0/(1E0+0.2316419E0*AX);                      00004060
185               DEN=0.3989423E0*EXP(-EX*EX/2E0);                 00004070
186               P=1E0-DEN*T*((((1.330274E0*T-1.821256E0)*T+1.781478E0)*T   00004080
                      -0.3565638E0)*T+0.3193815E0);                00004090
187               P=(P-0.5E0)*2E0;                                 00004100
                                                                   00004110
188           END NDTR;                                            00004120
                                                                   00004130
                                                                   00004140
189           END SED;                                             00004150
```

HAMILTON HARBOUR STUDY '74

section C

Dispersion

HAMILTON HARBOUR STUDY
SECTION C
DISPERSION

SUMMARY

A CLUSTER OF THREE DROGUES WERE TRACKED FOR THREE HOURS UNDER DIFFERENT WIND CONDITIONS IN THE EASTERN PORTION OF THE HARBOUR AT A DEPTH OF 2M BELOW THE WATER SURFACE. MEASURED EFFECTIVE DISPERSION COEFFICIENT RANGED FROM 1.7 TO 10^3 CM^2/SEC. THE MEASURED EFFECTIVE DISPERSION COEFFICIENTS AS A FUNCTION OF TIME BEHAVED IN THE SAME MANNER AS OTHER GREAT LAKES STUDIES. THE EFFECTIVE DISPERSION COEFFICIENT OF 1.2×10^4 CM^2/SEC USED IN THE NUMERICAL MODEL AFTER 1974 REPORT FOR 40 HOURS WAS FOUND TO BE REASONABLE.

HAMILTON HARBOUR STUDY

DISPERSION (MULTIPLE DROGUES)

INTRODUCTION

In the application of the two dimensional model it was
necessary to use a dispersion coefficient. The dispersion
coefficient used consisted of two parts, namely a constant
part due to wind stress, and a variable part related to
local current speed, depth and bottom roughness. Sensi-
tivity runs were carried out on the model using values of
0 and 9.3×10^3 cm²/sec for the wind generated part of the
coefficient. In general the lower value of wind generated
dispersion caused numerical instability problems while the
larger value produced more meaningful results when the model
was compared to water quality survey results. Dispersion
coefficients ranged from 0 to 1.2×10^4 cm²/sec in the
numerical model. The upper value is within the limits deter-
mined by dye injection experiments near the lakeshore. It
is also compatible with the apparent horizontal dispersion
coefficients in the range 10^4 to 10^6 cm²/sec for length
scales of 1-10 km and model runs for 48 hours to 25 days.
used by Simons (1972) for his Lake Ontario model. To ensure
that the absolute value for dispersion did not adversely
affect a numerical solution the same value for the disper-
sion coefficient was used in the comparison of alternatives.
While it is known that the wind generated portion of the
dispersion coefficient should not be assumed constant
throughout the numerical grid or constant with respect to
time it was not practical to evaluate the dispersion coeffi-
cients at numerous locations in the Harbour simultaneously.
Consequently these assumptions were necessary. Whether the
values assumed for the dispersion coefficients were reason-
able and whether the dispersion coefficient behaves in an
expected manner as a function of time could be checked in a
qualitative manner. This work was undertaken in 1974.

Three similar drogues (2 aluminum sheets 1 m² at right
angles suspended from a small surface float) were set at 2 m
below the surface and released from a common point at the
same time. The positions of the drogues were determined at
various times after release. The separation of the drogues
from their center of mass (centroid of fixed locations) was
determined graphically for each time that the drogue loca-
tions were known. The variance (σ^2) of these distances was
then an estimate of the dispersion or the apparent horizontal
dispersion coefficient $\varepsilon = \sigma^2/2t$ where t = time. The drogue
release was repeated at well off-shore locations (water
depth approximately 12 m) at the eastern and western ends of
the Harbour on different days in July. Wind records during
the drogue releases are presented in Table I.

RESULTS AND DISCUSSION

Computations of the apparent horizontal dispersion coef-
ficients and variances for each of the runs are presented in
Table 2. Plots of the log variance versus log time and log
dispersion coefficient versus log time are presented in
Figures 1 and 2 with the statistically determined best-fit
straight lines. The slope of the log variance versus log
time is 2.04 which is similar to the results of Okubo and
Farlow (1967) who used multiple drogues (50 to 90) at depths
of 1.5 to 6 m on lakes Erie and Michigan and found a slope
of 2.0. Well it is obvious that estimating dispersion
coefficients by tracking the separation of three drogues can
at best be a crude approximation (subsequently drogue
experiments used 4 and 5 drogue clusters), the results for
the variance compare favourably with other more extensive
experiments. And it appears that horizontal dispersion as
measured by drogue clusters in Hamilton Harbour exhibit the
same growth rate with time as open lake experiments. It is
also noteworthy that Okubo comments that "the expected
tendency of the group size to increase with time was not
always noticed". A similar situation is apparent in this
limited experiment in Table 2.

An apparent dispersion coefficient of 1.2×10^4 cm^2/sec is
not attained until a time of 50 hours on the fitted line and
it falls within the 95% confidence intervals at 4.8 hours
according to the drogue experiments. However, the longest
period of drogue tracking was 2.5 hours so that dispersion
coefficients of 1.2×10^4 cm^2/sec is not occuring until well
beyond the limits of the experiment. Okubo and Farlow
(1967) whose experiments extended for nearly 5 hours found
the log variance to grow with time at the more rapid rate of
3 in the period 1.5 to 5 hours. Consequently one would
expect 1.2×10^4 cm^2/sec to occur after shorter periods of
time approximately 16 hours (or 2 hours for the 95% confi-
dence intervals). It appears that for model runs of 20
hours and more in the Hamilton Harbour report (May 1974) a
horizontal dispersion coefficient of 1.2×10^4 cm^2/sec is
not unreasonable.

REFERENCES

Okubo A. and J. S. Farlow 1967. Analysis of some Great
Lakes drogue studies. Univ of Michigan, Proc 10th Conf
Great Lakes Res, 294-308

Simons T. J. 1972. Development of numerical Models of Lake
Ontario: Part 2. Univ of Michigan, Proc 15th Conf Great
Lakes Res, 655-672.

TABLE 1

HAMILTON HARBOR 1974
WINDS

| Date | Time | Winds | | Drogue |
		Dir. From	Speed m/sec	Tracking
July 5	0600	225	3.57	
	0700	270	4.46	
	0800	270	5.36	
	0900	270	5.80	start
	1000	270	6.24	
	1100	270	6.69	
	1200	270	6.24	stop
	1300	270	5.36	
July 9	0600	225	3.24	
	0700	225	3.13	
	0800	270	3.13	
	0900	270	3.13	
	1000	225	3.57	start
	1100	270	4.46	
	1200	270	6.24	stop
	1300	270	6.24	
July 10	0800	0	3.57	
	0900	0	2.68	
	1000	0	3.57	
	1100	0	4.46	
	1200	0	3.57	start
	1300	45	2.24	
	1400	0	2.68	
	1500	45	3.57	stop
	1600	0	4.01	

TABLE 2

HAMILTON HARBOR 1974
MULTIPLE DROGUES

Date	t Time secs. x 10^3	σ^2 Variance cm^2 x 10^6	$\varepsilon = \sigma^2/2t$ cm^2/sec
July 5	1.98	1.12	283
	5.58	11.3	1015
	8.82	3.2	182
July 9	1.71	0.07	260
	3.6	1.41	1953
	5.7	5.0	4390
July 10	2.1	0.49	117
	4.86	3.16	305
	8.88	6.39	360
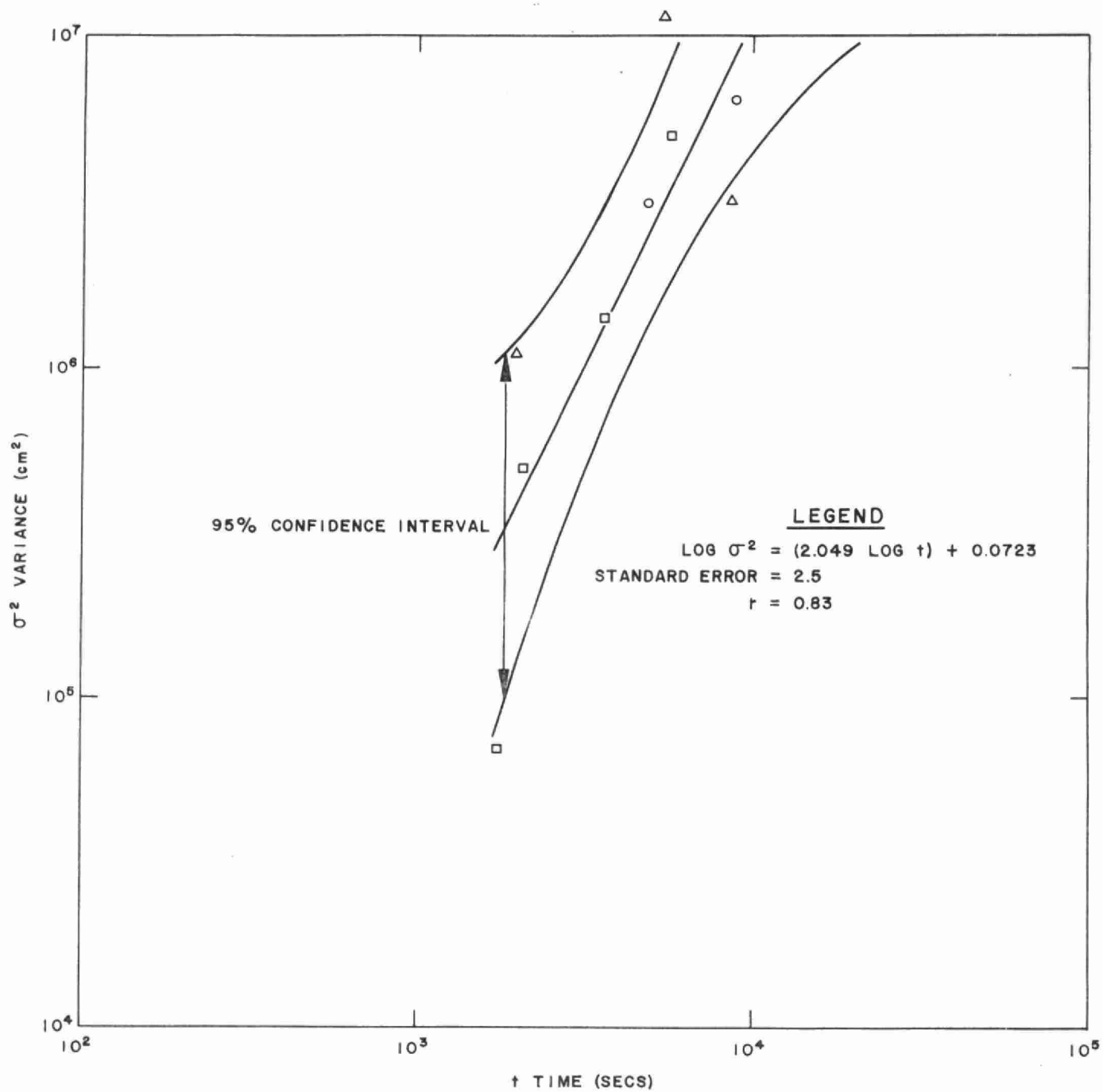
FIG. 1 – MULTIPLE DROGUES JULY 1974
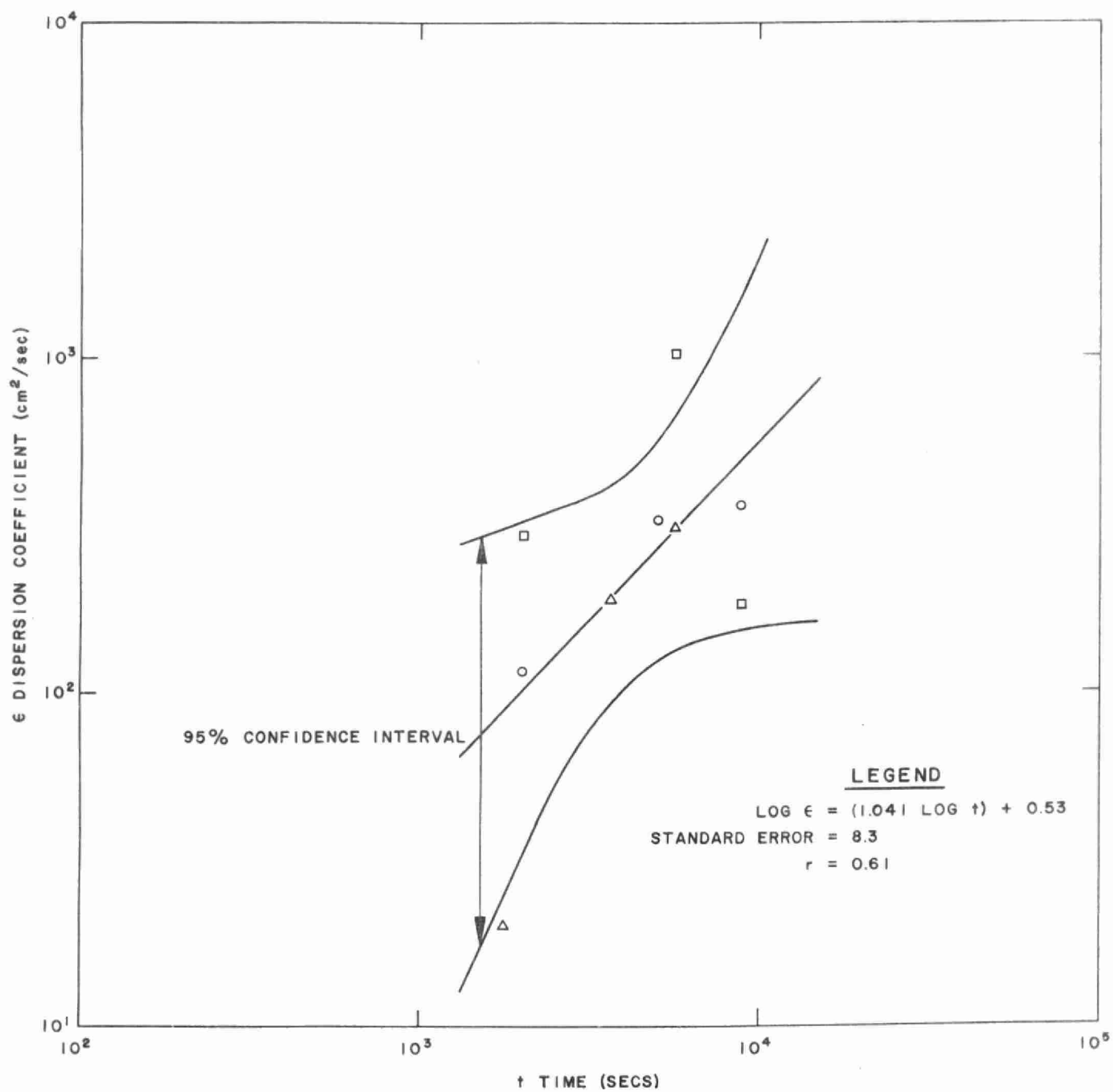
FIG. 2 - MULTIPLE DROGUES JULY 1974

HAMILTON HARBOUR STUDY '74

section D

Periodicities and mass
exchange through
Burlington ship canal

HAMILTON HARBOUR STUDY

SECTION D

PERIODICITIES AND MASS EXCHANGE
THROUGH THE BURLINGTON SHIP CANAL

SUMMARY

PERIODICITIES RELATED TO SEMI-DIURNAL AND LAKE OSCILLATION
EFFECTS WERE OBSERVED IN THE RECORDS OF WATER CHEMISTRY
AND CURRENT METER DATA OBTAINED IN THE CANAL AND HARBOUR
DURING 1974. THESE PERIODICITIES RANGED FROM 12 HOURS TO
20 MINUTES AND INFLUENCED THE INTERPRETATION OF WATER
QUALITY DATA COLLECTED BY CONVENTIONAL SURVEY TECHNIQUES.

ANALYSIS OF CURRENT DATA OBTAINED IN THE CANAL FOR A
10 DAY PERIOD IN THE ABSENCE OF THERMAL STRATIFICATION
INDICATED A NET EXCHANGE TO THE LAKE OF APPROXIMATELY
10 PERCENT OF THE HARBOUR VOLUME. A SIMILAR EXCHANGE RATE
TOWARDS THE HARBOUR WAS OBSERVED DURING A PERIOD OF
THERMAL STRATIFICATION; HOWEVER, THE PRESENCE OF A COMPLEX
FLOW REGIME FREQUENTLY INCLUDING THREE LAYERS OF DIFFERENT
TEMPERATURE AND CONDUCTIVITY INCREASES THE UNCERTAINTY OF
THIS ESTIMATE. NEVERTHELESS, THESE ESTIMATES INDICATE THE
OBVIOUS IMPORTANCE OF THESE EXCHANGE MECHANISMS IN MAIN-
TAINING HARBOUR WATER QUALITY.

HAMILTON HARBOUR PERIODICITIES AND MASS
EXCHANGE THROUGH THE BURLINGTON SHIP CANAL

INTRODUCTION

As part of the Hamilton Harbour Study (MOE, 1974), recording
water chemistry and current meters were operated at two
depths in the Burlington ship canal during 1972 and 1973.
The data obtained indicated that water motion in the harbour
and ship canal is a complex phenomenon. In the ship canal
non-stratified periods were characterized by alternating
flows of harbour water to the lake and lake water into the
harbour with periods corresponding to semi-diurnal and lake
oscillation effects. In times of stratification, these
motions were combined with simultaneous outflow of warm
harbour water above inflowing lake water and even occasional
inflow of lake water above harbour water. In addition, high
frequency variations of periods 0.1 to 0.2 hr, likely due to
harbour oscillations, have been observed.

Within the harbour, currents and water quality were also
found to be influenced by both harbour and lake oscillations.
These motions produced temporary displacement of the thermo-
cline of up to several meters, rendering the interpretation
of grab sample data difficult and necessitating the use of
numerical averaging techniques in determining stocks of
nutrients, dissolved oxygen, and other chemical substances.

In 1974, the instrumentation program was extended to include
six pairs of recording current and water quality meters.
The purpose of this program was to provide a synoptic data
set suitable for calibration and verification of a three-
dimensional numerical model. In addition, an improved
estimate of mass exchange and periodicities in the ship
canal was desired. This section discusses the results of
this latter phase.

EXPERIMENTAL PROGRAM

In 1974, six installations, each consisting of one current
meter and one water chemistry meter were operated in June
and July. These installations occupied four distinct
geographical locations, shown in Figure 1. Two of these
(the ship canal, M1 and M2, and the offshore location, M6
and M7) consisted of installations at two different depths.
As in 1972-73, shore-mounted Schneider robot monitors were
operated on the ship canal (installations M1 and M2). These
units measured temperature, conductivity, dissolved oxygen
and pH, and were supplied by submerged pumps located 3.6 and
6.7 meters from the bottom. Recording current meters were
operated at the same depth and locations. The depth separa-
tion was less than desired to measure the mass exchange
between the harbour and the lake in a two layer system, but

was dictated by the wave activity in the ship canal. The
instrument separation did measure the two-layered system in
the canal on some occasions and was supplemented by depth
profiling.

Submerged water quality and current meters were also used in
the Ottawa St. Slip (installation M5) and the southeast
corner (Windermere Basin, installation M8) in order to
document the variation of water quality from the major
industrial discharges and the Hamilton Water Pollution
Control Plant, for input to the numerical model.

In addition, water chemistry was measured at two depths in
the eastern end of the harbour (installations M6 and M7),
using NERA recording water quality meters. These instruments
consist of submerged sondes employing Hydrolab sensors which
monitor the same parameters recorded by the Schneiders, as
well as depth and oxidation-reduction potential. The signals
are amplified and recorded on a surface-mounted digital
recording package. Two such units were supported from a
Braincon plank-on-edge-buoy.

RESULTS

As the methods of data analysis are identical to those used
in 1972-73 (MOE, 1974), they will not be repeated here.

Means and standard deviations of water chemistry data
obtained in 1974 are summarized in Table 1. Unfortunately,
not all meters functioned during any one time interval. The
intervals for which most meters functioned were June 25 to
July 5 and July 16 to 22. Almost complete data was obtained
from the ship canal for both intervals. On the other hand,
complete data were obtained only for the first interval from
Windermere Basin, and the second interval at the offshore
location. The meter at the Ottawa St. Slip produced only 27
hours of usable data immediately after installation.

A statistical summary of 1974 current meter results is given
in Table 2, and current meter measurements are compared with
drogue trackings in Table 3. At the Ottawa St. slip, all
meter speed readings were lower than the drogue readings by
a factor of 2 to 5. This was due to slime and oil debris
fouling the rotor, despite several cleanings. The time
average speed is thus expected to be between 10 and 20
cm/sec. The Windermere Basin record is characterized by
greater than 50% negligible (< 0.3 cm/sec) currents. Although
the results do not correspond exactly to current meter
reading, the drogue trackings indicates low speeds (less
than 2 cm/sec, except for July 2, when drogue results may
have been influenced by a 20-25 mi/hr wind from the west).
Drogue comparisons for the upper offshore location (M6) were
fairly good (speed readings on the meter tended to be
somewhat faster than those observed during drogue tracking).

No record was obtained from the lower current meter at the same location (M7). All other current meters performed satisfactorily in 1974. These results emphasize the difficulty of generating a synoptic (instantaneous spatial water quality description) data set by operating a large number of instruments simultaneously.

Means of the along channel component of current data from the ship canal for one month periods varied from 1.5 to 8 cm/sec; corresponding standard deviations were 2 to 11 cm/sec (1.0 to 1.5 of mean). The large relative standard deviations reflected the alternating directions of flow within the canal.

Figures 2 and 3 show examples of the depth distribution of temperature and conductivity measured at different times with bathythermograph casts and conductivity meters. Three layers of differing temperatures were frequently observed during periods of thermal stratification. This could possibly represent outflow of two layers of stratified bay water plus lake water inflow, or other similar combinations, however, with the instrumentation used, a detailed explanation is impossible. The complexity of the depth distribution in the canal cannot be adequately described with only two recording chemistry meters during periods of strong stratification and unsettled conditions. However, it was possible to use the current meter records to estimate harbour-lake exchange rates by avoiding very active periods (high winds and velocities) and stratified periods when the chemistry meters did not sample both the epilimnion and hypolimnion.

The significant (95 percent confidence level) periods appearing in the auto-variance density spectra have been summarized in Tables 4 and 5. The data in Table 4 are a summary of the spectral densities observed using all data sets obtained in 1973 and 1974. Not every data set exhibited all these periodicities at the 95 percent confidence level; however, these periodicities were present in some data sets at the 95 percent confidence level and in most data sets at the 80 percent confidence level. Periods longer than one hour were not always resolved for a measuring interval of 10 min, but were obtained upon analysis of the data averaged over 30 min intervals. A typical example illustrating the strong periodicity observed in the ship canal appears for dissolved oxygen in Figure 4, and for currents in Figure 5. Typical variance density plots for dissolved oxygen and currents at an offshore harbour location appear in Figures 6 and 7 respectively. As fewer records are available in the harbour for shorter intervals of time, all spectral periods occurring at the 80 percent confidence level are presented in Table 3 to facilitate comparison with canal data.

In the previous report (MOE, 1974), the canal periodicities were compared with theoretical lake oscillation periods

calculated by Rockwell (1966). Since then, Rao and Schwab (1974), and Freeman, Hamblin, and Murty (1974) presented theoretical calculations of periods of Lake Ontario and the Helmholtz mode for Hamilton Harbour. The periodicities calculated by Rao and Schwab shown in Table 4 compare very well with the observed data. Unfortunately, the presence of the 2.0 hr period is indicated by only a small number of data sets, and does not really confirm its existence. Some shorter periods are visible; although these may be higher longitudinal modes or transverse modes of oscillation, it is impossible to verify their nature.

In addition, a period of 2.5 hr (recalculated as 2.3 hr using average 1973-74 water levels) has been calculated for the Helmoholtz or pumping mode for Hamilton Harbour (Freeman, Hamblin and Murty 1974). This mode arises from the presence of the canal, which is an opening in the harbour with a width much less than the harbour dimensions. Such an opening induces an additional gravitational mode of a period much longer than the fundametal mode. This gravitational mode increases to infinity as the width of the opening is decreased to zero.

The observed period of 2.4 hr (Tables 4 and 5) may be due to either the third free oscillation of Lake Ontario or the Helmholtz mode of Hamilton Harbour. However, it is possible that the period of 2.0 hr observed at both depths in the offshore harbour location (Table 5), but only seen very rarely in the 1973 chemistry data in the canal (Table 4), may be due to the Helmholtz mode.

Significant cross correlations between water chemistry and currents in the canal and the offshore location are given in Table 6, and significant cross correlations of water chemistry between upper and lower levels at the above locations are presented in Table 7. The presence of a large number of significant cross correlations between chemistry and currents attests to the common mechanism responsible for their period- icities. However, the reason for the lack of many signifi- cant coherences between chemistry and currents at the offshore location is not known.

Chemistry is generally not correlated between the two levels at the offshore location due to the strong thermal stratifi- cation that was present. On the other hand, the complex flow regime in the canal, combined with the instrument spacing used (Figure 3), produced significant coherences between the two levels in the canal.

CALCULATION OF MASS EXCHANGE

The current meter records were examined in order to estimate a value for mass exchange in the canal. During some periods of stratification the complex nature of the flow regime

prevented the estimation of any meaningful value for mass exchange.

During a period of no thermal stratification (Figure 2) but periodic flows (September 26 to October 6, 1973) using the 10 minute readings of velocity, one finds a net mass flow of 2.7×10^4 kg/sec towards the lake. Mean flows in each direction were approximately 10.6×10^4 kg/sec persisting for 3.2×10^5 sec towards the harbour and 5.3×10^5 sec towards the lake. This represents a mass flow of 3.4×10^{10} kg (3.4×10^7 m^3) of water towards the harbour and 5.7×10^{10} kg (5.7×10^7 m^3) of water towards the lake in 10 days. The net exchange to the lake in these 10 days is approximately 10 percent of the harbour volume indicating the importance of the ship canal in maintaining harbour water quality. The exchange dilutes chemical constituents in the harbour and provides dissolved oxygen for the bottom sediments and chemical oxygen demand discharges. A similar analysis of mass exchange for June 13 to July 22, 1974 indicates a mean mass flow to the lake of 3.5×10^4 kg/sec and to the harbour of 6.1×10^4 kg/sec. The net exchange is 2.6×10^4 kg/sec to the harbour, or 1 percent per day of the harbour volume. However, as this estimate was obtained during a period of strong thermal stratification, it is subject to a larger amount of uncertainty than the first estimate. At any rate, these estimates indicate the magnitude of exchange which does occur through the ship canal.

The important observation is that actual records are required in a numerical model for the harbour (MOE, 1974, section E) if it is to be representative of the processes. While the annual throughput is approximately 80 percent per year, the periodic exchange may be of the order of 10 percent in 10 days. The magnitude of these exchange mechanisms makes it difficult to statistically determine reductions or increases in harbour stocks of material. An example of the importance of the effects is indicated in Section E, Dissolved Oxygen Uptake where it is shown that the amount of dissolved oxygen entering Hamilton Harbour through the ship canal is important in satisfying chemical oxygen demand loadings and sediment oxygen demands.

Considering the importance of the ship canal in maintaining harbour water quality, it is important that any future development of an outer harbour in Lake Ontario be constructed in such a manner that the exchange through the canal will not be significantly reduced. Prior to any work being undertaken, it is desirable that proposed projects be tested in some exchange model and the results be incorporated into an environmental impact statement demonstrating that the developments will not reduce the harbour-lake exchange.

The 1974 survey program attempted to generate a synoptic

data set at depth by operating six pairs of water quality and current meters concurrently. These six pairs of data sets would provide a time history of the principal inputs to the model (the two largest waste discharges and the harbour-lake exchange), as well as an offshore location in the harbour, for model verification purposes. Presently it is difficult to obtain a concurrent record at six locations with all sensors working in a calibrated condition when checked against in situ samples. Until this technology is perfected it is unlikely that meaningful predictions of water chemistry can be made for the coastal regions.

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TABLE 1: Means and Standard Deviations of 1974 Water Chemistry in Hamilton Harbour as measured by Recording Water Quality Meters

Location	Time Period	# of Readings	Temperature ($^{\circ}$C)		Dissolved Oxygen				pH		Conductivity (umhos/cm at 25°C)	
					mg/l		% Sat.					
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Upper Canal (6.7 m from bottom) (M)	June 27-July 4	1013	15.7	3.1	7.8	2.3	78	21	7.9	0.3	455	56
	July 16-22	844	12.5	2.3	9.6	1.7	89	13	8.0	0.2	401	37
Lower Canal (6.7 m from bottom) (M2)	June 29-July 12	1896	9.9	3.1	10.2	1.1	90	10	8.1	0.2	367	34
	July 16-22	845	8.9	1.7	11.6	1.1	99	9	8.1	0.1	354	22
Upper Offshore (15.7 m from bottom) (M6)	July 11-22	513	22.2	1.2	7.6	1.6	87	19	7.9	0.3	518	9
Lower Offshore (6.6 m from bottom) (M7)	June 25-July 5	482	14.1	0.8	-	-	-	-	-	-	501	11
	July 11-22	512	12.6	0.7	1.3	0.9	12	9	7.4	0.1	461	12
Ottawa St. Slip (M5)	June 25-26	27	28.3	1.0	5.0	1.2	64	15	-	-	677	10
Windermere Basin (M8)	June 25-July 9	2007	21.0	1.6	4.1	2.0	46	23	-	-	603	46

TABLE 2

Summary of Current Meter Results

PERIOD	JUNE 1974					JULY 1974				
Location	M1	M2	M5	M6	M8	M1	M2	M5	M6	M8
Resultant Speed (cm/sec) (Veetor average)	1.48	6.70	6.41	2.89	0.97	6.66	10.85	4.46	1.77	1.09
Resultant Direction covering from (degrees)	82	74	190	159	166	66	33	190	161	169
Period of Negligible** Speed (% of recording time)	3	2	8*	26*	60	5	2	35*	19*	48
Average Speed (cm/sec)	8.13	10.28	6.87	3.77	1.04	7.80	12.54	4.69	3.57	1.39
Maximum Speed (cm/sec)	43	41	27	13	9	40	41	18	13	11
Persistence	0.18	0.65	0.93	0.77	0.93	0.85	0.87	0.95	0.50	0.79
Total No. of readings	2448	3102	4874	4888	2304	2448	3103	5057	6247	3099
Interval between readings (minutes)	10	10	5	5	10	10	10	5	5	10

*   < 2.0 cm/sec

** < 0.30 cm/sec

TABLE 3

DROGUE MEASUREMENTS
HAMILTON HARBOUR, 1974

Location	Date	Time	Drogue		Meter	
			Direction (going to)	Speed (cm/sec)	Direction (going to)	Speed (cm/sec)
Ottawa St.	June 26	15.20	20°	10-12	15-35°	1.9
Slip (M5)	June 27	12.15	20°	10-11	28°	2.7
	July 2	11.45	25°	11-12	11°	4.2
	July 9	11.00	25°	11-12	10°	4.7
	July 10	13.30	29°	6-10	5-30°	1.6
	July 16	11.00	29°	8-9	15-30°	5.0
Upper offshore	June 26	13.45	342°	3-5	327°	7.3
location (M6)	June 27	11.10	337°	3-5	325°	2.2
	July 9	11.55	15°	3	30°	4.7
	July 10	14.30	332°	4	355°	6.7
	July 16	12.00	115°	0.5	330°	3.0
Windermere	June 26	15.00	–	0	308°	0.4
Basin (M8)	June 27	12.00	357°	0.7	10°	0.2
	July 2	12.15	106°	2-6	200-205°	1.0
	July 9	11.30	49°	2	–	0.
	July 10	13.45	340°	1	–	0.

TABLE 4

THEORETICAL AND OBSERVED (1973-4)
PERIODICITIES IN HOURS IN THE
BURLINGTON SHIP CANAL (95% confidence)

Theoretical Lake Ontario (Rao & Schwab 1974)	Chemistry (Dissolved oxygen, pH and conductivity) OBSERVED		Currents (along canal)	
	Upper	Lower	Upper	Lower
–	16	12	12	12
5.11	4.6 to 5.3	5.0 to 5.3	5.0	5.0
3.11	3.2	3.2 to 3.4	3.2	3.2
2.31	2.2 to 2.4	2.3 to 2.5	2.4	2.2 to 2.4
1.87	1.95 to 2.0	–	–	–
1.78	1.65 to 1.75	1.65 to 1.75	1.7	1.7
1.46	1.4 to 1.45	1.4 to 1.45	1.35 to 1.4	1.35 to 1.45
–	1.2	1.25	1.25	1.25
–	1.0	1.0	1.0	1.0
–	0.80 to 0.85	0.75 to 0.85	0.86	0.84
–	0.65 to 0.70	0.63 to 0.67	0.67	0.67
–	0.53 to 0.59	0.52 to 0.57	0.56	0.55
–	0.43 to 0.47	0.44 to 0.46	0.43 to 0.47	0.47
–	0.38 to 0.39	0.38 to 0.41	0.37	0.37 to 0.38
0.35*	0.35 to 0.36	0.35 to 0.38	0.35	0.35

NOTE:* Predicted first mode for Hamilton Harbour, using Merian
equation. Periods less than 0.5 hr., were observed by
analyzing unsmoothed data.

Not all periods were observed at the 95% confidence level
in any one data set; however, spectral density concentrations
at the 80% level or lower were generally observed in each
data set for most periods greater than 3 times the measur-
ing interval.

TABLE 5

OBSERVED PERIDOICITIES IN HOURS
HAMILTON HARBOUR, 1974 (80% Confidence)

Theoretical Lake Ontario (Rao and Schwab, 1974)	Ottawa St. Slip (M5) Currents	Offshore Location Upper (M6) Currents	Offshore Location Upper (M6) Chemistry	Offshore Location Lower (M7) Chemistry	Windermere Basin (M8) Currents	Windermere Basin (M8) Chemistry
5.11	5.5	–	4.8 to 5.3	4.8 to 5.3	–	–
3.11	3.2	3.4	3.2 to 3.4	–	–	3.0
2.31	2.4 to 2.7	–	2.4 to 2.8	2.5 to 2.7	2.6	–
1.87	–	–	1.9 to 2.0	–	2.0	–
1.78	–	–	–	1.8 to 1.85	1.7	1.65 to 1.8
1.46	–	–	1.3 to 1.45	1.4 to 1.55	1.38	–
	–	1.25	–	–	1.18	–
	–	–	1.1 to 1.15	1.1 to 1.15	1.08	1.11
					–	0.81
					–	0.68
					–	0.50
					–	0.44

Note: Current meter peaks are a composite of peaks observed in the north-south and east-west directions.

TABLE 6: Significant Cross Correlations between Water Chemistry and Currents, Hamilton Harbour, 1974.

Location	Date	Temperature	Dissolved Oxygen	pH	Conductivity	# of Data Points
Burlington Ship Canal Upper (6.7 m from bottom) (M1)	June 27- July 4	1.2-10.	1.25-5.0	2.5-5.0	1.2-2.0	1019
		*3.3(25)	*4.0(-157)	*5.0(-161)	*5.0(15)	
		*2.5(18)	*2.5(173)	*2.9(-171)	*3.3(8)	
		*1.67(40)	*1.67(-165)		*2.2(-1)	
		*1.43(1)		1.67(174)	*1.67(7)	
					*1.43(-27)	
		0.95-1.00(-4)	1.25(166)		*1.25(-32)	
		0.83-0.87(-24)	1.00(103)		1.00(-73)	
		0.48(-153)			0.83(-82)	
Burlington Ship Canal Upper (6.7 m from bottom) (M1)	July 16-22	2.2-9.	2.7-13.	none	2.0-13.	844
		*4.5(9)	*13(-154)		*4.4(10)	
		*3.0(19)	*5.3(-173)		*3.0(18)	
		*2.2(14)	*3.0(-168)		*2.2(-17)	
		1.78(-18)			1.78(-29)	
		1.45(5)				
Burlington Ship Canal lower (3.6 m from bottom (M2)	June 29- July 12	1.2-6.0	1. -12.		1.3-12.	1896
		*4.0(41)	*4.8(-146)	4.8(-134)	*12(1)	
		*2.2(16)	*2.2(-176)	2.4(173)	*4.0(19)	
		*1.71(2)	*1.71(-171)		*2.4(2)	
		*1.41(10)			*1.71(3)	
		0.86(-29)	1.04(143)		*1.41(-24)	
			0.86(142)		0.98(-38)	
					0.83(-41)	
Burlington Ship Canal lower (6.7 m from bottom) (M2)	July 16-22	3.0-5.3	4.5(-170)	4.5(-166)	4.5(16)	845
		*4.5(14)				
		*3.3(19)				
Upper Offshore Location (15.7 m from bottom (M6)	July 11-22	none	none	14.(-151)	1.71(172)	513
				1.13(164)		

NOTES: Along channel component is used for ship canal locations. North component is used for offshore location. Indicated figures are the periods in hours for 5 percent significant coherences (Panofsky and Brier 1968), followed in parentheses by the phase angle in degrees.

*Asterisks indicate periods of maximum coherence within the period (stated immediately above) in which coherence is significant throughout.

TABLE 7: Significant Cross Correlations of 1974 Water Chemistry between Upper and Lower Levels, Burlington Ship Canal and Offshore Location, Hamilton Harbour

Location	Date	Temperature	Dissolved Oxygen	pH	Conductivity	# of Data Points
Ship Canal	June 29– July 5	1.18-6.7	2.2-6.7	2.2-3.3	1.25-6.7	755
		*2.86(-6)	*5.0(-15)	*2.9(0)	*2.9(-2)	
		*1.67(-9)			*1.67(-10)	
		*1.43(14)	1.25-1.82		*1.33(-20)	
		1.00	*1.43(-21)			
		0.80(62)				
Ship Canal	July 16-22	3.0-6.0	4.0-6.0	4.8-6.0(-2)	3.0-6.0	845
		*4.8(22)	*4.8(20)		*4.8(23)	
Offshore	July 11-22	none	4.8(-35)	none	none	512

Note: Indicated figures are the periods in hours for 5 percent significant coherences (Panofsky and Brier 1968) followed by the phase angle in degrees.

* Asterisks indicate periods of maximum coherence within the period (stated immediately above) in which coherence is significant throughout.
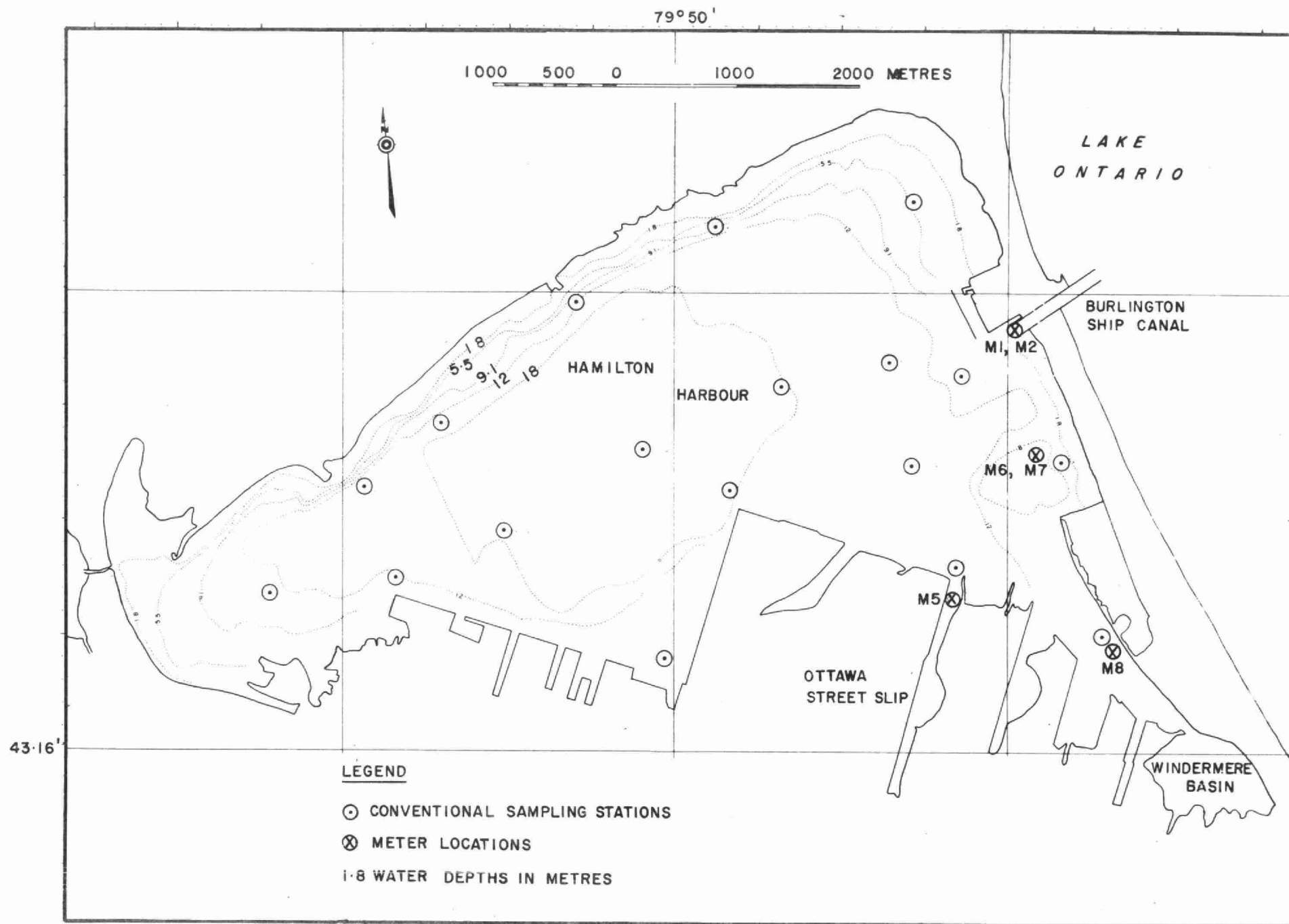
FIGURE: I HAMILTON HARBOUR SAMPLING AND METER LOCATIONS
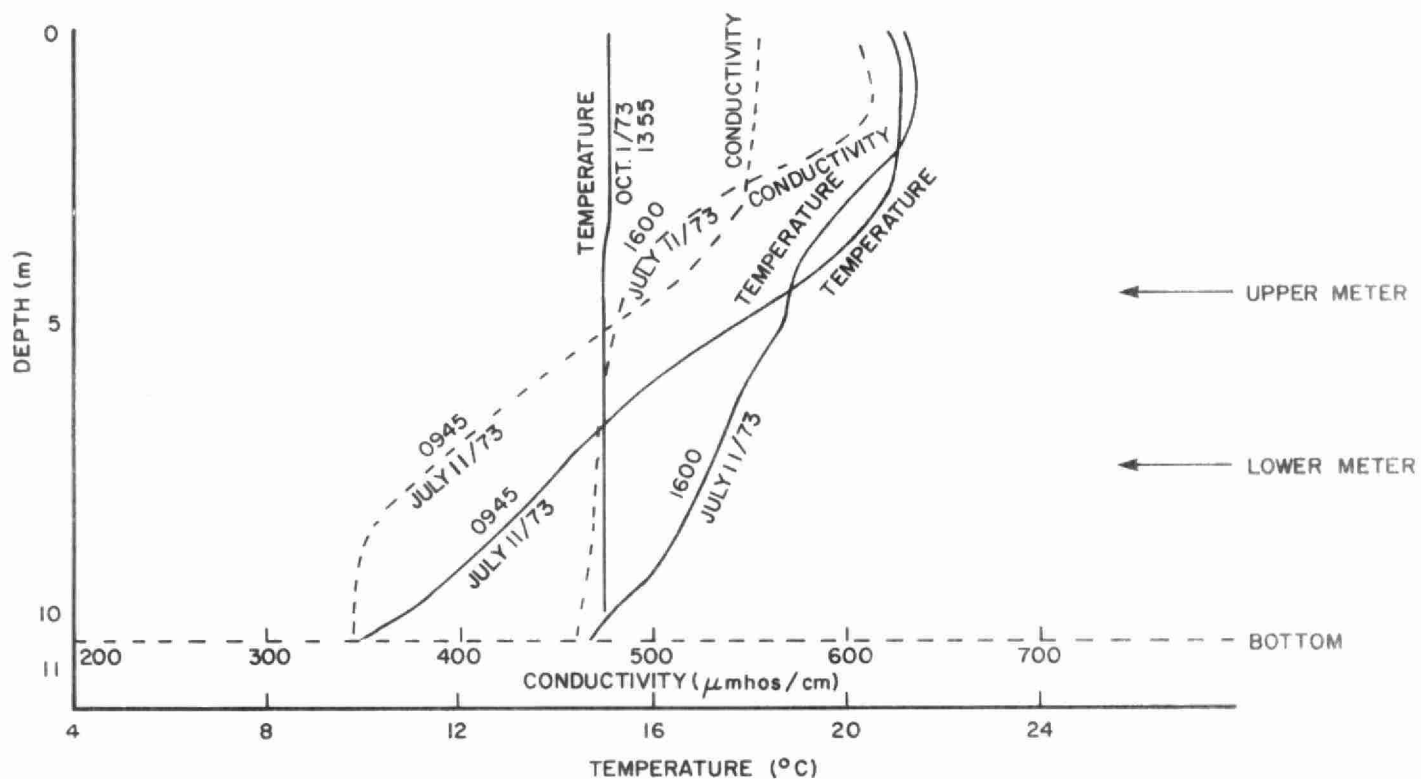
FIGURE: 2 DEPTH PROFILES OF TEMPERATURE AND CONDUCTIVITY
BURLINGTON SHIP CANAL, JULY II AND OCTOBER I, 1973
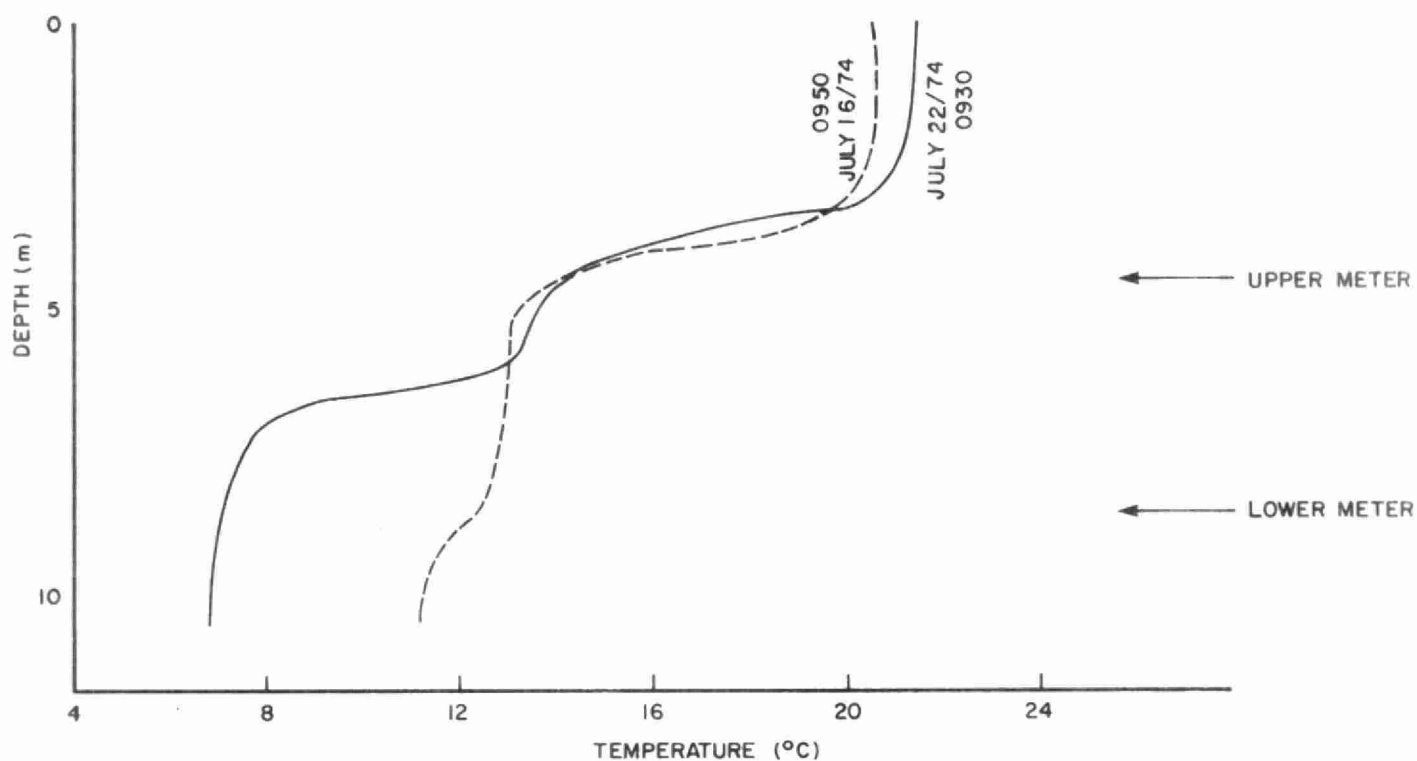
FIGURE: 3 DEPTH PROFILES OF TEMPERATURE BURLINGTON SHIP CANAL,
JULY 16 AND 22, 1974

FIGURE 4 : AUTO VARIANCE DENSITY SPECTRA FOR DISSOLVED OXYGEN (MG/L) SHIP CANAL 6·7m ABOVE BOTTOM FOR JUNE 25 – JULY 5, 1974
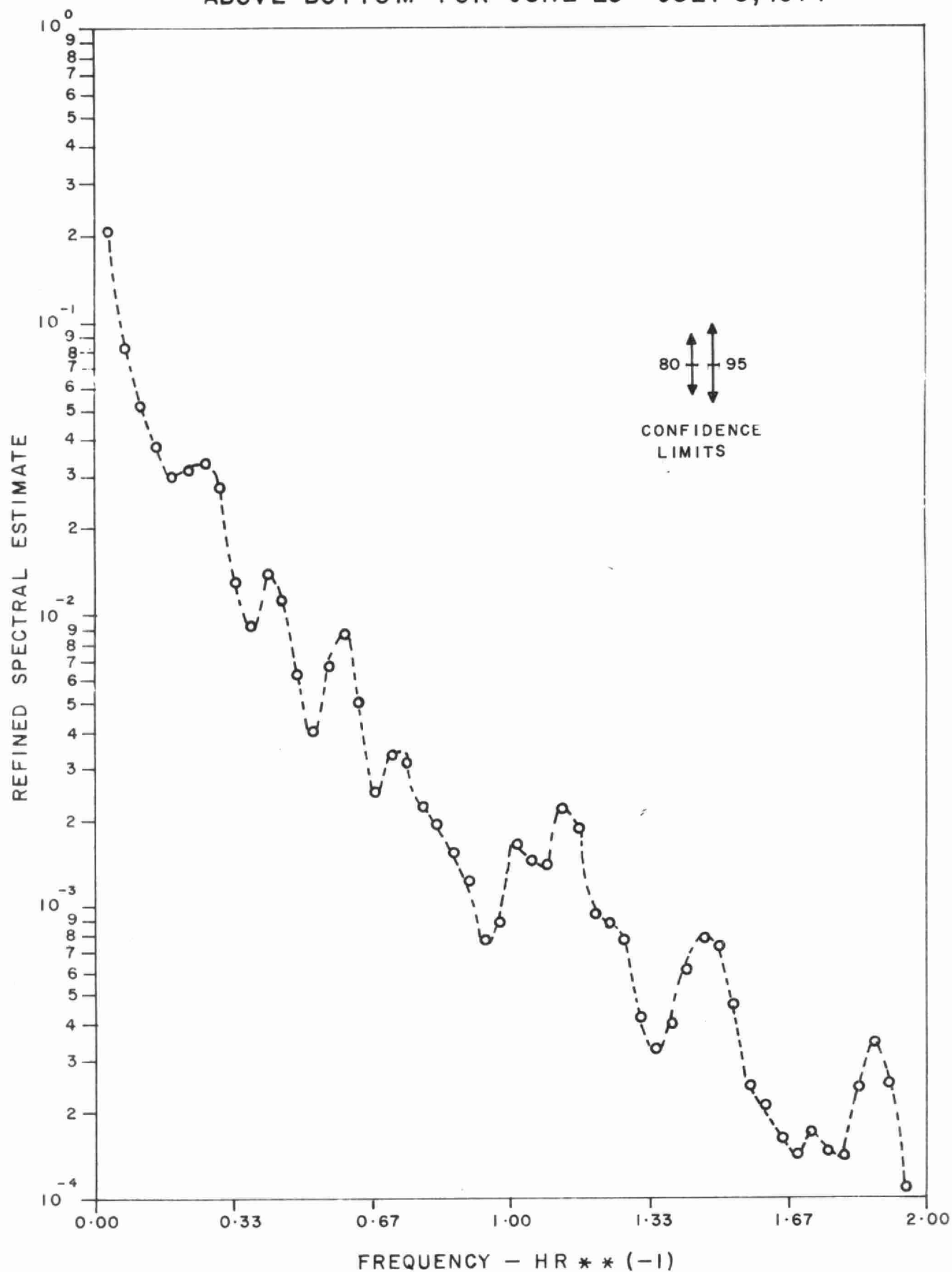
FIGURE 5 : VARIANCE DENSITY SPECTRA FOR
SHIP CANAL CURRENTS JULY, 1974

FIGURE 6 - VARIANCE DENSITY SPECTRA FOR DISSOLVED OXYGEN (MG/L) LOCATION M7, JULY 11-22/74

FIGURE 7 – VARIANCE DENSITY SPECTRA FOR CURRENTS
ALONG RESULTANT DIRECTION (160°)

OFFSHORE LOCATION (M6) JUNE 14 – JULY 22/74
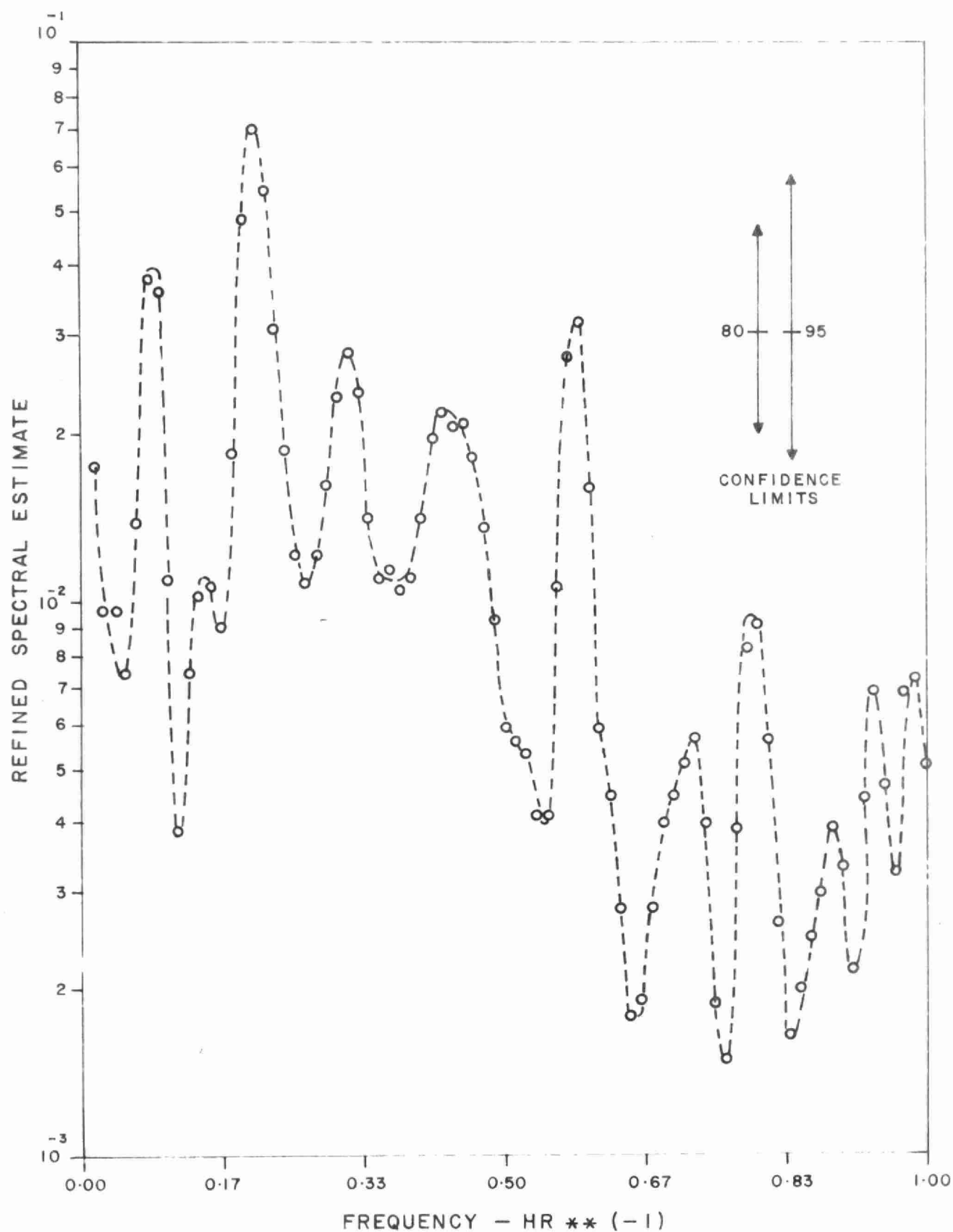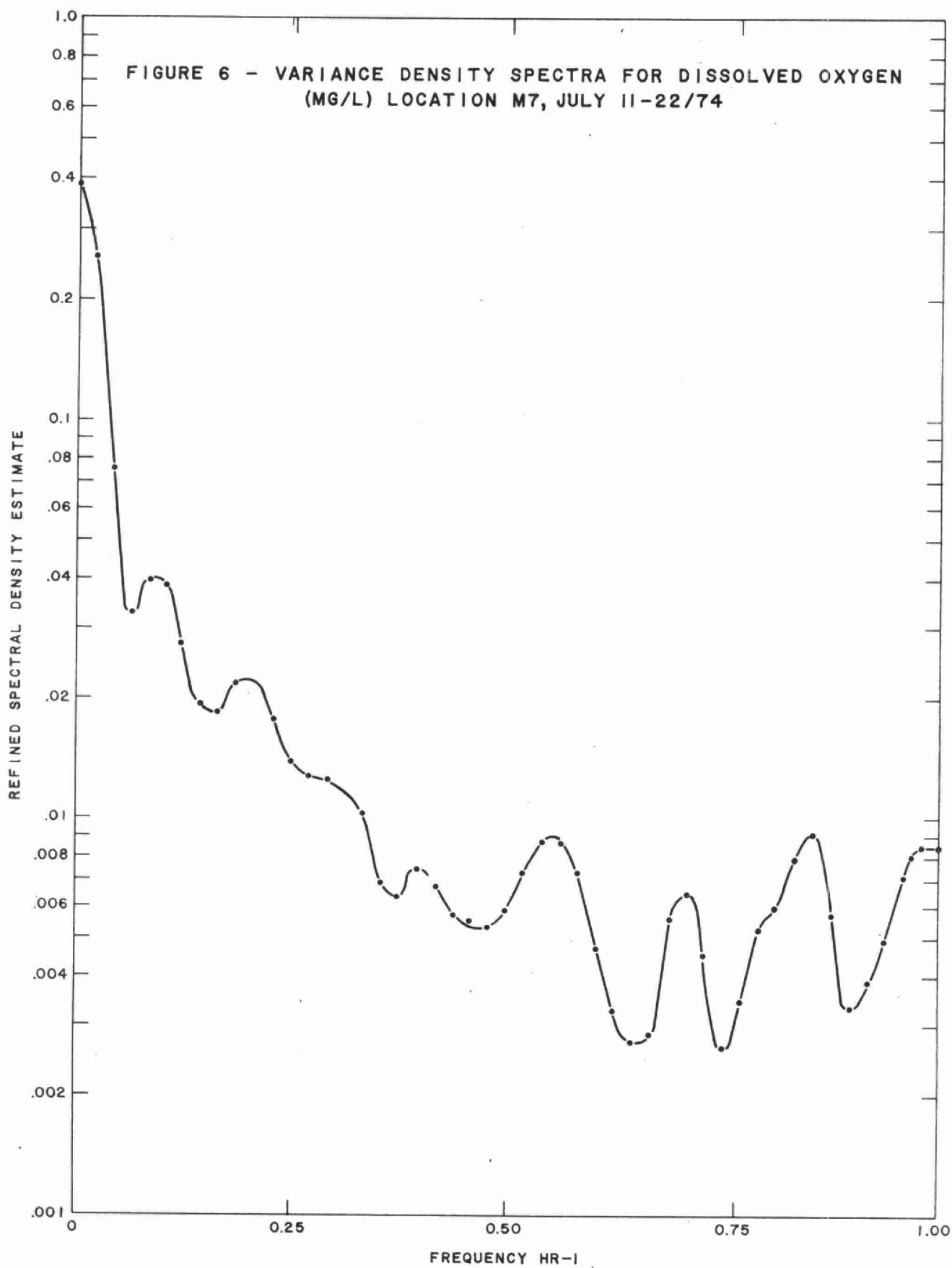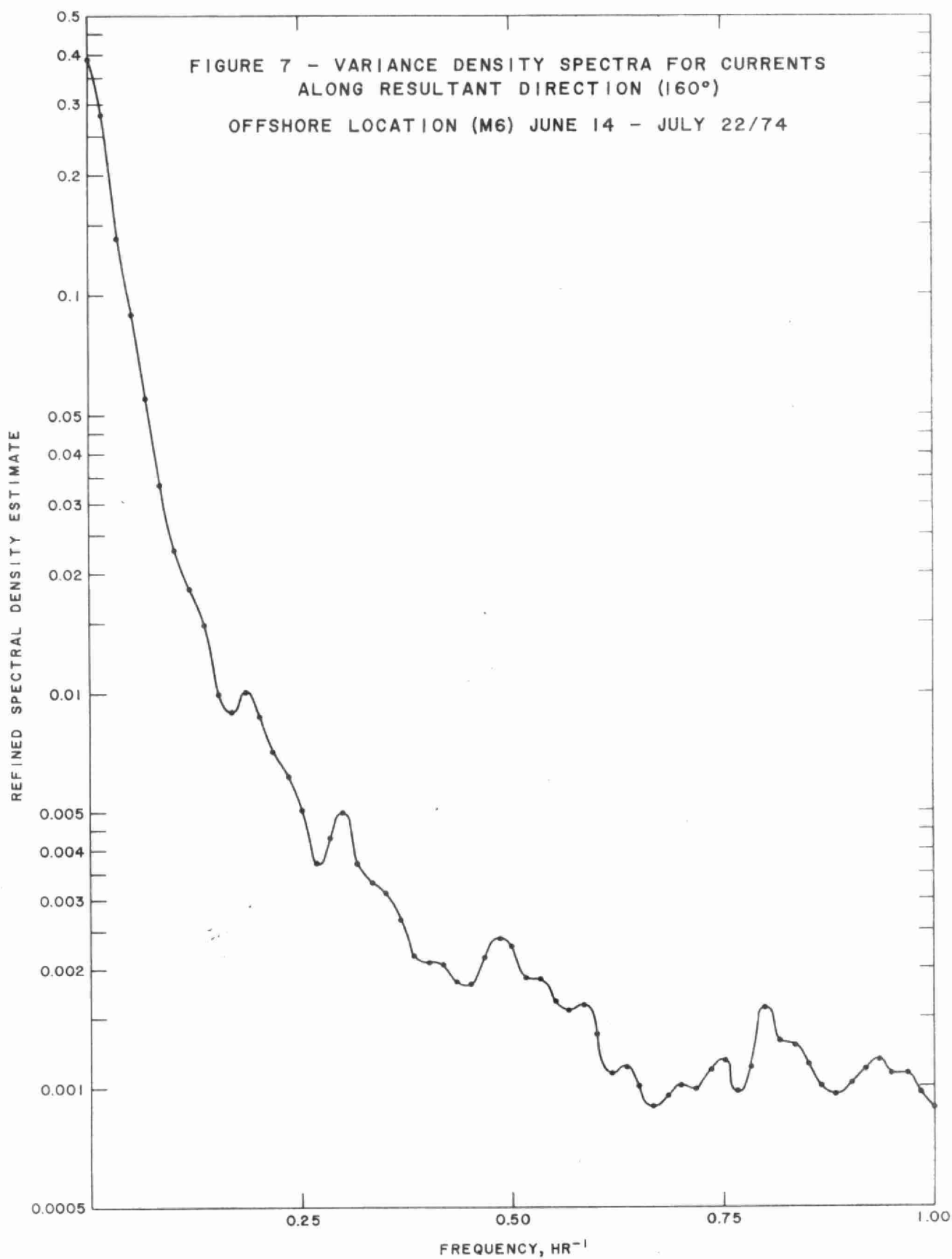
HAMILTON HARBOUR STUDY '74

section E

Sediment dissolved oxygen uptake

HAMILTON HARBOUR STUDY

SECTION E

SEDIMENT DISSOLVED OXYGEN UPTAKE

SUMMARY

A REVIEW OF LITERATURE DATA ON IN SITU AND LABORATORY METHODS OF MEASURING SEDIMENT OXYGEN UPTAKE IS PRESENTED. EFFECTS ON OXYGEN UPTAKE RATE OF ORGANIC MATTER CONTENT, SEDIMENT DEPTH, SEASON AT WHICH SEDIMENT WAS COLLECTED, BACTERIAL COUNT, MACROINVERTEBRATE POPULATION, AND DISSOLVED OXYGEN CONCENTRATION OF THE OVERLYING WATER ARE DISCUSSED.

THE DISSOLVED OXYGEN DEPLETION CURVE WITH TIME IN 1972 IS DISCUSSED IN TERMS OF UPTAKE RESULTS MEASURED ELSEWHERE. FOR A 109 DAY PERIOD, AN ESTIMATED VALUE OF OXYGEN UPTAKE WAS 3×10^6 KG, AS COMPARED TO AN OBSERVED DEFICIT (COMPUTED FROM OBSERVED AND SATURATION DISSOLVED OXYGEN STOCKS) OF 1.5×10^6 KG. A MAJOR REASON FOR THE DIFFERENCE BETWEEN THESE FIGURES IS BELIEVED TO BE MASS EXCHANGE THROUGH THE BURLINGTON SHIP CANAL. ESTIMATES OF THE MAGNITUDE OF DISSOLVED OXYGEN SUPPLIED TO THE HARBOUR RANGE FROM 4×10^6 KG.

DAILY DISCHARGES OF BOD AND COD TO THE HARBOUR ARE ABOUT THREE TIMES THE ESTIMATED SEDIMENT OXYGEN UPTAKE. THIS DISCREPENCY IS DISCUSSED IN TERMS OF EPLIMNETIC REAERATION AND PHOTOSYNTHETIC OXYGENATION.

SEDIMENT OXYGEN UPTAKE IN
HAMILTON HARBOUR

As part of the 1972 Hamilton Harbour Study (MOE, 1974), it
was found that dissolved oxygen levels below 5 mg/l existed
in the hypolimnion from July to September, and in many
places, anoxic conditions were approached. In July 1974,
average dissolved oxygen concentrations recorded in the
hypolimnion of the east end of the harbour remained below
2.5 mg/l for 11 days, and were frequently below 1.0 mg/l
(Section A). It was estimated that about two-thirds of the
deficit was caused by discharges and sediment demand and
one-third by recent phytoplankton decay in August. In the
report it was recommended that chemical oxygen demand (COD)
loadings be reduced by approximately 60 percent, in order to
reduce oxygen deficits.

As the oxygen demand of the sediments is an important factor
in determining what improvement in dissolved oxygen deficit
might be expected from reductions in COD loadings, this
factor should be measured to clarify the effects of existing
bottom sediments. This section begins with a review of
existing literature data on sediment oxygen demand. The
situation in Hamilton Harbour is then discussed with respect
to the literature data, and suggestions for experimental
work are made.

Equipment used in Oxygen uptake Studies

Three basic types of experiments have been used in oxygen
uptake measurements. These are: (a) in situ studies, (b)
laboratory studies on quiescent systems, and (c) laboratory
studies using well agitated samples in the Warburg apparatus.

In Situ Studies

Stein and Dennison (1967), and later, Edberg and Hofsten
(1973) used cylindical plexigalss units for in situ oxygen
uptake studies. The cylinder used by Edberg and Hofsten was
300 mm in diameter and 220 mm in height, and bore an outer
flange 40 mm from the lower edge of the cylinder. This
flange rests on the mud surface, and the entire unit is
anchored by weights or steel rods. The oxygen uptake is
measured with an oxygen electrode (Yellow Springs Instruments
Beckman), with a stirring motor being employed to provide an
adequate water flow past the electrode without stirring up
the sediment. Although Stein and Dennison used divers to
deploy their equipment and remove any trapped surface water
by fanning, Edberg and Hofsten employed divers only in the
case of a rough bottom. The latter authors used a movable
lid which closes on the bottom to ensure that representative

bottom water was trapped. A similar apparatus was also used
by Hunter et al (1973).

As a portion of project Hypo, an intensive survey of the
Lake Erie central basin hypolimnion conducted in 1970, Lucas
and Thomas (1972), as well as Blanton and Winklhofer (1972),
measured Lake Erie sediment oxygen demand with in situ
plexiglass chambers. The former authors used a triangular
prism-shaped chamber which covered 0.25 m^2 of bottom and
enclosed 12 ℓ of water. A submersible pump circulated the
water with minimum sediment disturbance. The latter authors
employed a box which enclosed 137 ℓ of water, covering 0.206
m^2 of bottom. Both types of chamber were equipped with fins
to prevent them from sinking into the soft Lake Erie sediments,
and in both cases, dissolved oxygen and temperature were
monitored continuously by recording meter systems.

James (1974) used two types of in situ respirometers to
measure sediment oxygen demand. The first consisted of a
metal box which was very similar to the chambers already
described. The other was a plastic tunnel 30 m long by 1 m
wide which could be anchored in a stream bed. Oxygen deple-
tion was measured by comparing the dissolved oxygen concen-
tration at the entrance and exit ends of the tunnel.

Laboratory Studies - Quiescent Samples

Several types of apparatus have been used in the laboratory
to attempt to simulate quiescent natural conditions, and at
the same time study the effects of variables such as tempera-
tures, initial oxygen concentrations and the presence of
other ions such as nitrate on the oxygen uptake rate. The
in situ studies of Stein and Denison (1967) and Edberg and
Hofsten (1973) were accompanied by laboratory investigations.

Hanes and Irwin (1969) used a Pyrex reactor 8.9 cm deep and
16.5 cm inside diameter covered with a plexiglass lid
through which a thermistor and oxygen electrode were inserted.
The water was circulated without stirring up the mud by
means of a magnetic stirrer placed in a petri dish at the
bottom of the reactor. A similar setup, employing wooden
aquaria, was used by Stein and Denison (1967); they determin-
ed oxygen by the Winkler method on siphoned water samples.

In their laboratory studies, Edberg and Hofsten (1973) used
plexiglass tubes 500 mm long and 70 mm in diameter, equipped
with a magnetic stirrer and a Yellow Springs oxygen electrode.
Similar tubes 19 or 29 cm in length were used in a series of
investigations at the Water Pollution Research Laboratory in
England (Knowles, Edwards and Briggs, 1962; Edwards and
Rolley, 1965; Rolley and Owens, 1967). These investigations
reacted six core samples in a cluster of tubes mounted on a
rotating platform. Oxygen was measured with a dropping

mercury electrode which was inserted into each tube in turn;
the water in each tube was stirred by a magnetic stirring
bar mounted on a perforated disk and driven by a rotating
magnet mounted in the center of the tube cluster.

Jenkin tubes were used by Hayes and McAuley (1959). These
consist of a glass tube equipped with a spring loaded brass
disk and rubber pad at the bottom, and are used with a
special apparatus (Mortimer, 1942) for in situ sampling of
mud cores. Oxygen was determined by the Winkler method.
Some screw capped bottles were also used by these authors.

Sediment samples were collected either directly in the
reaction tubes, or by use of an Ekman dredge. In the case
of dredge samples, the reaction tube was loaded with sediment
by plunging directly into the dredge. Lake water was then
carefully introduced into the tube, in order not to disturb
the sediment, and aerated for a period of time before begin-
ning the experiment.

Laboratory Studies-Agitated Samples

Several authors (Liu, 1973; Gardner and Lee; 1965) have used
a manometric technique using the Warburg respirometer.
Sediment and water are shaken in 125 ml flasks. Carbon
dioxide is absorbed using 10% KOH solutions and oxygen
uptake is measured manometrically. This apparatus is well
suited for measuring maximum uptake rates, with results
indicating a factor of approximately ten times more oxygen
absorbed with shaking compared to without. However, for our
purposes, this measurement is not desired; thus these tests
will not be further discussed.

Results of Oxygen Uptake Studies

Some results obtained using the equipment already described
are given in Table 1. For ease of comparison, all rates
have been expressed in gO_2/m^2-hr and recalculated to $15°C$
using the relation (Edwards and Rolley, 1965)

$$t = \frac{1}{T2-T1} \quad \ln \frac{C_2}{C_1}$$

where C_2 and C_1 are the oxygen uptakes at temperatures T_2
and $T_1 °C$; t is the temperature coefficient (assumed = 0.07).
This temperature coefficient corresponds well to that measured
by Edberg and Hofsten (1973) between 10 and $20°C$; however,
they found a larger coefficient at lower temperatures. In
view of the difficulty in obtaining accurate oxygen uptake
results as well as the changes that may occur prior to
performing laboratory experiments, this temperature coeffi-
cient can be regarded as a satisfactory approximation over
the experimental range of 0 to $25°C$.

Oxygen uptake results have been compared according to a number of factors. Among these are organic (or volatile) matter, season of collection, bacteriological counts, sediment depth, presence of ions such as nitrate, addition of macroinvertebrates, etc.

(a) Organic Matter

Most authors have attempted to relate oxygen uptake rates to organic matter (or carbon) content of sediments. Most authors have measured organic matter content as loss on ignition of dried sediment at 500 - 600°C. Rolley and Owens (1967) and Edwards and Rolley (1965) measured organic carbon by converting $CaCO_3$ to $CaSO_3$ by a 24 hour pretreatment with SO_2 gas, followed by oxidation of organic carbon to CO_2 at 600°C. Organic carbon measured in this fashion correlated with loss in ignition with a correlation coefficient of 0.923, indicating a highly significant relationship.

In general, oxygen uptake increases with increasing organic content of sediments. This can be illustrated by the data obtained on Swedish lakes (except as indicated) by Edberg and Hofsten (1973), summarized as follows:

Source	Organic Matter (% dry weight)	Oxygen Uptake Rate (g/m^2-hr at 15°C)
Lake	1.3	0.02
Rivers	8-11	0.04 - 0.15
Lake	12.2	0.1
Baltic Sea, Pulpmill effluent site	11.4 - 17.7	0.04 - 0.13
Eutrophic Lake	30 - 40	0.15 - 0.18

Although no significant difference occurs between the oxygen uptakes of the samples with 8 to 18% organic matter, a marked effect of organic content is indicated by the samples with 1.3 and 30-40% organic matter. For celluosic fiber sludge deposits with an organic matter content of 80-95% in the top 1-2 cm, and 10% beneath the top layer, Stein and Denison (1967) obtained an uptake rate at 15° of 0.20 g/m^2-hr. Due to the extreme gradient in organic content, this result is difficult to assess, but it is obviously suggestive of an increased uptake caused by the high surface organic content.

In reasonable agreement with Edberg and Hofsten, Rolley and Owens (1967) obtained oxygen uptakes of 0.05 - 0.06 g/m^2-hr for river muds of average 11% loss on ignition, and 0.10-0.14 g/m^2-hr for river muds (affected by sewage) of average 15-21% loss on ignition. Edwards and Rolley (1965) present

a graph in which oxygen uptake is clearly independent of organic carbon over a range of 4 to 13% C. This represents an approximate range of organic matter of 8 to 26%, somewhat greater than the similar range of no significant difference evident from the results of Edberg and Hofsten (1973).

Recently, Hunter (1973) reported a comprehensive study of factors determining oxygen uptake rates of benthal stream deposits. The organic content of the muds was determined in terms of total organic carbon, COD, BOD (5 day and 20 day), hexane extractable, hexane-benzene extractable, and total volatile solids. Oxygen uptake rates were 0.05 to 0.5 g/m^2-hr and total volatile solids ranged from 5 to 15%. The significance of the various parameters in determining benthal oxygen demand was explored by multiple regression. However, most of the coefficients calculated were unexplainable; some were even negative, and all eight together explained less than 70% of the variation. Even the variable with the highest degree of correlation (COD) explained only 37% of the variations.

These results show that although large variations of organic content exert an influence on oxygen uptake rates, other factors play important roles in producing the observed large variations in uptake rate.

(b) Sediment depth

The effect of sediment depth on oxygen uptake, as measured in the laboratory, can provide an indication as to how deep beneath the surface oxygen can be taken up in a natural system in the absence of scouring action.

In the laboratory portion of their study in cellulosic fiber sludge, Stein and Denison (1967) found no effect of sediment depth on oxygen uptake using sediment depths of 2.5 and 5.1 cm. Likewise, Edwards and Rolley (1965) found no effect of depth on oxygen uptake in sediment depths between 2.1 and 10.2 cm.

From experiments with sewage sludges, Baity (1938), and Fair, Moore and Thomas (1941) suggested that oxygen uptake was approximately proportional to the square root of the depth for depths between 0.1 and 10 cm. The former authors combined the effect of organic matter concentrations in using the areal concentration of organic matter as a parameter. Although the organic content of their sludges was similar to that used by Stein and Denison, the sludges of the former authors were settled only briefly prior to the experiment, and moreover were subject to considerable agitation due to anaerobic decomposition and consequent release of gas bubbles. On the other hand, the river and lake sediments used by most authors have been accumulated over long periods of settling; deeper mud tends to exert less oxygen demand as indicated by

some "dummy Jenkins" experiments (Hayes and McAuley, 1959), and is more resistant to bacterial decomposition than surface mud (Allen, Grendley and Brooks, cited by Edwards and Rolley, 1965).

In a situation like Hamilton Harbour, the effect of bottom scour, which is prevented by the apparatus in any in situ study, would probably be greater than that of mud depth. On the other hand, depth tests might prove interesting if laboratory work were undertaken.

(c) Season at which sediment was collected

The effect of seasons has only been investigated in laboratory studies (Rolley and Owens, 1967; Edwards and Rolley, 1965). Although the former authors found that oxygen uptake in the summer was only very slightly greater than that in the winter, the latter investigators found a definite seasonal effect with maximum uptake obtained from samples taken in the spring and summer and minimum uptake from winter samples. The reason for the difference is suggested to the seasonal changes in population of micro and macro invertebrates.

(d) Bacterial count

While Hayes and MacAuley (1959) reported a linear relationship between bacterial count and oxygen consumption in lake muds, Edwards and Rolley (1965) found no dependence of oxygen uptake on bacterial count. Possibly other organisms or chemical substances might be important in the sediments studied by Edwards and Rolley. Perhaps the effect of mud sterilization should be investigated in a laboratory study; however, the process of sterilization would probably result in chemical changes in the mud. Perhaps potassium cynide or formalin could be used to inhibit biological activity and differentiate chemical from biological oxidation (Liu, 1973).

(e) Macroinvertebrate population

As a result of the lack of significant correlation between sediment chemistry and oxygen uptake, Hunter et al (1973) extended the study to include the effect of macroinvertebrate population. A very significant relationship between oxygen demand and tubificid (tubifex) worm population was obtained, with the oxygen demand increasing from 0.07 to 0.48 g/m^2-hr as the tubifex worm population increased from 4300 to 284,000/m^2. After allowing a correction for oxygen demand of sediments devoid of macroinvertebrates, a demand per worm was calculated as 0.032 mg/worm/day. As this was about five times the respiration rate of the worms, other factors such as their burrowing action bringing organics to the surface may be important. In addition, the sediment contained 1700 to 13,000 bloodworms/m^2, which were not considered in the

calculation but should be significant. Although their estimation of a demand per worm may thus be incorrect, their results illustrate the significant effect of the macroinvertebrate community in determining oxygen uptake.

The 1972 bottom fauna survey in Hamilton Harbour showed the presence of more than 11,000 oligochaetes (tubificidae)/m^2 throughout most of the harbour, with very little area containing less than 1,100/m^2. Considering the effect of these organisms on sediment oxygen uptake as illustrated by Hunter et al (1973), any experimental program must be accompanied by a bottom fauna enumeration. If laboratory studies are done the uptake of sediments containing macroinvertebrates should be compared with that of sterilized sediments.

(f) Other variables

Edwards and Rolley (1965) studied the effect of nitrate concentration in the overlying water on oxygen uptake. They found that increased nitrate concentration up to 20 mg/l N had no effect on oxygen uptake.

Several investigations considered the dependence of uptake rate on oxygen concentration, using an equation of the form $R=aC^b$ where R is uptake rate, C is oxygen concentration, and a and b are empirical constants. Edwards and Rolley (1965) found that the oxygen uptake data fit this equation; Edberg and Hofsten (1973) stated their data obtained from laboratory measurements did not fit this equation, although they present a graph which should apparently fit it. Their in situ data, obtained for a shorter time at DO concentrations above 7 mg/l, on the other hand, give a rate independent of oxygen concentration.

Lucas and Thomas (1972) also presented some data which show an effect of oxygen concentration on uptake rate. Oxygen uptake rates, corrected to $15^{\circ}C$, decreased from 0.08-0.14 g/m^2-hr at DO concentrations of 7-9 mg/l, to 0.05-0.06 g/m^2-hr at DO concentrations of 3 mg/l. A further decrease in DO content, however, did not result in any further drop in the oxygen uptake rate.

The effect of sunlight causing photosynthetic oxygen production was noted by Lucas and Thomas (1972) in Lake Erie. They measured oxygen uptake rates in situ using clear and black plexiglass chambers in August 1970 at various times of the day. Although the rate in dark chambers was constant at 0.05-0.06 g/m^2-hr ($15^{\circ}C$), the rate in light chambers varied diurnally, being similar to that in dark chambers at night but as low as zero during the daylight hours. At that time of the year, there was sufficient sunlight penetration to the lake bottom to permit algae to grow there, or allow

surface algae to remain viable after settling to the bottom.

The considerably lower uptake rate measured by Blanton and
Winklhofer (1972), also in Lake Erie as a part of Project
Hypo, must have been influenced by algal photosynthesis of
oxygen. Although algae were stated to be growing only
outside the box, microscopic algae may have been growing
within the box. Blanton and Winkelhofer, in stating that
their rate is comparable to the "integrated daily rate" of
Lucas and Thomas (which includes photosynthetic effects),
admit that their rate was influenced by photosynthesis.
Certainly, these results indicate how widely variable the
observed oxygen uptake rates can be under apparently similar
conditions.

Comparison of in situ and laboratory results

While Stein and Denison (1967) found a higher oxygen uptake
in laboratory experiments as compared to in situ results,
Edberg and Hofsten (1973) found a lower uptake in the laboratory.
Results of the latter, when corrected for temperature,
tended to be lower by a factor of as much as two or three
than the in situ results. As well, their laboratory results
increased by a factor of about two if the sediments were
stored under aerated water. Their explanation of this
difference is that respiring organisms multiply or become
better adapted to the new environment during storage, or
that burrowing organisms may increase active surface area.
Certainly, removal of the sediment has a decided effect on
its biological activity, and this effect could be different
for sediments of different nature, as is the case in the two
in situ investigations.

The observed differences in Lake Erie sediment oxygen uptake
results (Lucas and Thomas, 1972; Blanton and Winklhofer,
1972) may also be viewed as partly due to modification of
the natural conditions produced by inserting closed boxes of
different dimensions. Although it is true that gelatinous
layers or microzones may be disturbed during deployment of
in situ equipment, it is felt that the in situ procedure is
the most direct and accurate method of measuring oxygen
consumptions of sediments.

Sediment Oxygen Uptake in Hamilton Harbour

In the 1972 study of the oxygen budget in Hamilton Harbour
(MOE, 1974), dissolved oxygen concentrations were measured at
eight sampling stations twice in the spring, and then weekly
from mid-July to mid-November. Locations of sampling stations
used are shown in Figure 1. Dissolved oxygen stocks were
calculated by vertical integration of the DO-depth profiles
at each station followed by summing over the entire harbour.
A plot of the dissolved oxygen stock thus obtained against
sampling date is reproduced in Figure 2. Error estimates

and a curve of saturation DO stock have also been included in Figure 2. This curve was analyzed in terms of the oxygen depletion processes. Computed from observed and saturation DO stocks with appropriate temperature considerations, the oxygen demand was approximately 0.7×10^6 kg in April, and 1.5×10^6 kg in August. If the oxygen demand in April is assumed to be a result of waste discharges and bottom sediments, and that the temperature coefficient of these processes is assumed to be $(1.046)^{\Delta t}$, where Δt is the difference between to be bottom temperatures in August and April, it is estimated that about 1.0×10^6 kg of stock, or two-thirds of the total demand, are used in August by waste discharges and bottom sediments. This estimate may now be compared with an estimate based upon oxygen uptake data already discussed.

Under conditions of 7 to 9 mg/l DO at $15^\circ C$, Lucas and Thomas (1972) determined oxygen uptake rates of 0.08 to 0.14 g/m^2-hr for the central basin hypolimnion of Lake Erie. For similar conditions in Swedish lakes and rivers containing 8 to 12% organic matter, Edberg and Hofsten (1973) determined oxygen uptake to be 0.04 to 0.15 g/m^2-hr. With river muds containing 4 to 13% organic carbon, Edwards and Rolley (1965) obtained an uptake rate of 0.035 to 0.14 g/m^2-hr. This rate was proportional to the 0.45 power of the DO concentration in the overlying water. As most of Hamilton Harbour contained 5 to 15% organic matter in 1964-5 (OWRC, 1966), these figures were selected as representing conditions similar to Hamilton Harbour. Under this assumptions, the following estimate may be made of oxygen uptake for the period April 28 - August 14, 1972 (109 days).

Recognizing that the oxygen uptake rate is a function of both temperature and dissolved oxygen concentration, the above period was divided into three intervals: April 28-May 31, June 1-30 and July 1-August 14. For the first interval, it can be assumed that the average bottom temperature and DO in Hamilton Harbour are $8-10^\circ C$ and 7-9 mg/l, respectively. According to Lucas and Thomas (1972), an approximate uptake rate under these conditions is 0.07 g/m^2-hr, which results in a total uptake for the harbour of 1.3×10^6 kg in 35 days.

For June, if one assumes that the bottom DO has dropped to 2 or 3 mg/l and the temperature is $12^\circ C$, the oxygen consumptions may be estimated as 0.05 g/m^2-hr, using Edwards and Rolley's (1965) function of overlying DO concentration. This gives an uptake of 0.8×10^6 kg for the harbour in 30 days.

In July and August, the bottom average DO and temperature were estimated to be 1 mg/l and $14^\circ C$, respectively. (The measured bottom DO average for August 6-7 was 1.3 mg/l for the entire bay (18 stations) and 0.5 mg/l for a subset of the 6 deepest stations). From the data of Edwards and

Rolley, oxygen uptake is 0.04 g/m²-hr, or 0.9 x 10⁶ kg for 44 days.

This gives a total estimate of oxygen uptake of 3 x 10⁶ kg for the 109 day period, which is certainly only an order of magnitude estimation due to the assumptions involved in the estimation, as well as the wide range of observed figures in the studies cited. This estimate can now be compared with the measured figures of DO stock and deficit, exchange through the canal and COD loadings to the harbour.

As indicated in Figure 2, the dissolved oxygen stock in Hamilton Harbour was 3 x 10⁶ kg in April 1972. Were it not for photosynthesis, reaeration, and mass exchange through the Burlington Canal, the entire stock would be depleted by August. That the observed deficit (compared to saturation) in August was 1.5 x 10⁶ kg, of which 0.5 x 10⁶ kg was assumed due to phytoplankton decay indicates the importance of oxygen restoring mechanisms in maintaining harbour dissolved oxygen stock.

A major source of oxygen to the harbour is mass exchange through the canal. Recording water chemistry and current meter data obtained in the canal were examined in an attempt to estimate values for mass exchange in the canal (See section D, mass exchange). Two estimates of dissolved oxygen mass exchange in the canal are as follows:

(a) Mass exchange in the absence of thermal stratification, but with periodic flows present: A 10 day period of current meter data recorded at 10 minute intervals indicated volume flows of 3.4 x 10⁷ m³ of water toward the harbour and 5.7 x 10⁷ m³ of water toward the lake. If harbour water contains an average of 6 mg/l DO and lake water 11 mg/l DO this represents a flow in 109 days of 4.1 x 10⁶ kg DO to the harbour and 3.7 x 10⁶ kg DO to the lake. The net flow is 0.4 x 10⁶ kg DO to the harbour.

(b) Mass exchange with thermal stratification present: A similar analysis of 39 days of recording current meter data indicated a volume flow of 20.6 x 10⁷ m³ of water to the harbour and 11.8 x 10⁷ m³ of water to the lake. Using the above estimated DO concentrations, estimates of DO mass flows of 6.3 x 10⁶ kg to the harbour and 2.0 x 10⁶ kg to the lake are obtained. The net flow is thus 4.3 x 10⁶ kg to the harbour.

These estimates represent volume flows of water of approximately 1 percent of the harbour volume per day in opposite direction. Thus the actual flow of dissolved oxygen to the harbour would be between these extremes, but likely towards the lower estimate, as the net direction of water movement is towards the lake. Moreover, as dissolved oxygen concentrations measured in the canal varied between extremes of less than

1 to 11 mg/l for harbour water, and 9 to 14 mg/l for lake
water (with the lowest figures occurring in mid to late
summer), actual mass flows will vary widely with time. In
addition, bathythermograph data indicated the presence of a
three-layer system at times within the canal. Although the
instruments used thus provide only a rough estimate of DO
mass flow, they do indicate that the DO exchange with the
lake can be large and is a factor in determining the dissolved
oxygen stock.

Another comparison of interest can be made with the industrial
and municipal COD and BOD loadings to the harbour. As
enumerated in 1972, daily loadings are 1.0×10^5 kg/day. By
comparison, the estimated daily sediment oxygen uptake for
May 1972 is 0.37×10^5 kg (calculated from estimates used
previously). Thus the daily discharges as about three times
the estimated sediment oxygen uptake as estimated for a time
when the bottom DO is relatively high. Several reasons for
this discrepancy may be enumerated. Firstly, only a portion
of the COD will be particulate and be deposited in the
sediments. The remainder will be assimilated by epilimnetic
oxygen from photosynthesis or reaeration, or emitted to the
lake through the canal. As most of the industrial discharges
are in the epilimnion, this dissolved COD will not contribute
to the critical hypolimnetic depletion observed during
stratification. When the proposed destratification project
is undertaken, this dissolved COD will be distributed through-
out the harbour and may contribute to hypolimnetic oxygen
deficits. However, as the low DO water will be continuously
circulated to the surface, much of this demand should be
satisfied by atmospheric **reaeration**. In addition, if the
particle size of suspended matter is large, much of the COD
will be deposited in the vicinity of the outfalls. This may
result in the accumulation of sediment to depths greater
than that which will be readily oxidized. It should be
recalled that sediment oxygen uptake is independent of
depths greater than about 2 cm in laboratory tests (Stein
and Denison, 1967; Edwards and Rolley, 1965).

Although these estimates present a rough picture of the
sediment oxygen uptake situation in Hamilton Harbour, there
are too many variables in the chemically and biologically
active systems studied to apply data obtained elsewhere
accurately to the situation existing in Hamilton Harbour.
It is therefore proposed that sediment oxygen uptake experi-
ments be performed during 1975 in Hamilton Harbour. Although
most attention should be paid to locations near the major
discharges, all portions of the harbour should be considered
as the numerical model has indicated the possibility of
particulates being carried in currents around the northeastern
corner to the north shore of the bay. Furthermore statistical
analysis of sediment chemistry (section B) has indicated
correlations between stations 20 and 269, and between 269
and 257. In order to interpret the oxygen uptake data,

sediment samples should be analyzed for organic carbon, COD, BOD and Kjeldahl nitrogen, and the bottom fauna present should be enumerated.

To investigate the possibility of sediments at greater depths exerting oxygen demand, core samples should be taken and oxygen uptake of individual sections studied in the laboratory. This is particularly important near the location of the proposed diffuser.

It must be recognized that in situ oxygen uptake experiments present considerable experimental difficulty and variability, as the examples from the literature illustrate. However, actual data should be more reliable than estimates based on other water bodies. If these data can be compared with measured harbour DO stocks and correlated with analyses of industrial wastes, it is hoped that an improved picture of dissolved oxygen status in Hamilton Harbour, and the effect of reductions of industrial loadings, could be obtained.

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TABLE 1: TYPICAL OXYGEN UPTAKE RESULTS

Sample	Conditions	Oxygen Uptake (g/m^2-hr)		Author	Comments
		(at temperature of measurement)	(reduced to $15^{\circ}C$)		
Rivers-8-11% organic matter	in situ 0-10°C	0.013-0.06	0.037-0.15	Edberg & Hofsten, 1973.	% organic matter by dry weight
Lake - 1.3% organic	in situ 14°C	0.02		Edberg & Hofsten, 1973	
Lake - 12.2% organic	in situ 17°C	0.01			
Lake - 30-40% organic (eutrophic)	in situ 5-7°C	0.075-0.1	0.15-0.18		Lab. values lower.
Baltic Sea-Pulpmill effluent site - 11.4 - 17.7% organic	in situ 13-15°C	0.04-0.13			
Cellulosic fiber sludge. Strait of Juan de Fuco.	in situ 11°C	0.15	0.20	Stein & Denison, 1967.	80-95% volatile matter in top 1-2 cm.
Control area, Strait of Juan de Fuca	in situ 11°C	0.046	0.060	Stein & Denison, 1967	Sludge depth >2.5 cm has no effect on uptake rate (det'd by lab test) Lab values higher.
Paper-waste sludge	Lab. 25°C / 20°C / 15°C	0.13 / 0.07 / 0.07	0.06 / 0.05	Hanes & Irvine, 1969.	∿58% volatile solids.
(a) River muds	Lab. 15°C	(a) 0.05 winter, 0.06 summer		Rolley & Owens, 1967.	(a) Org. C = 6% dry LOI = 11%
(b) River muds affected by sewage	DO = 7 mg/l	(b) 0.10 winter 0.10-0.14 summer			(b) Org. C = 7-12% LOI = 15-21%
River muds	(a) Lab. 20°C	(a) 0.035-0.14	0.05-0.20	Edwards & Rolley, 1965	Seasonal effect - max. O_2 uptake in spring, summer, min. winter. 40% O_2 consumption due to macroinvertebrates. O_2 consumption approximately proportional to (DO) 0.45.
Org. C=4 to 13%	(b) 20°, high speed stirring, SS ∿ 4500 ppm	(b) 1.2	0.85		

Sample	Conditions	Oxygen Uptake $(g/m^2\text{-hr})$		Author	Comments
		(at temperature of measurement)	(reduced to $15^\circ C$)		
River muds (a) organically polluted (b) less polluted.	Lab.	(a) 0.3-0.9 (b) 0.01		Knowles, Edwards & Briggs, 1962.	Temperature not stated.
Lakes Montague, Southport, PEI	Lab (Jenkin)	0.03-0.04	0.04-0.05	Hayes & MacAuley, 1959	Dummy Jenkins results lower.
A number of other Maritime lakes.	Lab Wankin, dummy J,bottle) all $\sim 11^\circ C$	0.006-0.02	0.008-0.026		Linear relation O2 cons. vs bacterial count with ~ 0.007 g/m^2-hr at zero bact.
Lake Erie bottom Sediment	In situ $9^\circ C$ DO = 4 mg/l	0.013	0.020	Blanton & Winklhofer, 1972.	Sunlight penetrated to bottom. Photosynthesis of algae occurring.
Lake Erie bottom Sediment	In situ $8-9^\circ C$ DO = 7-9 mg/l	0.05-0.09	0.08-0.14	Lucas & Thomas 1972	Bottom not stirred or slightly stirred.
Lake Erie bottom Sediment	In situ $9-9.5^\circ C$ DO = 3 mg/l	0.03-0.04	0.05-0.06	Lucas & Thomas, 1972	Darkened chamber, or night results.
Lake Erie bottom Sediment	In situ, $11-14^\circ C$ DO = 0.5-1.7 mg/l	0.04-0.06	0.04-0.08	Lucas & Thomas, 1972.	Results in datime with clear chambers are lower.
Passaic River, New Jersey	In situ, temperature not stated	0.05-0.5		Hunter et al, 1973	Results interpreted in terms of tubifex (sludgeworm) respiration
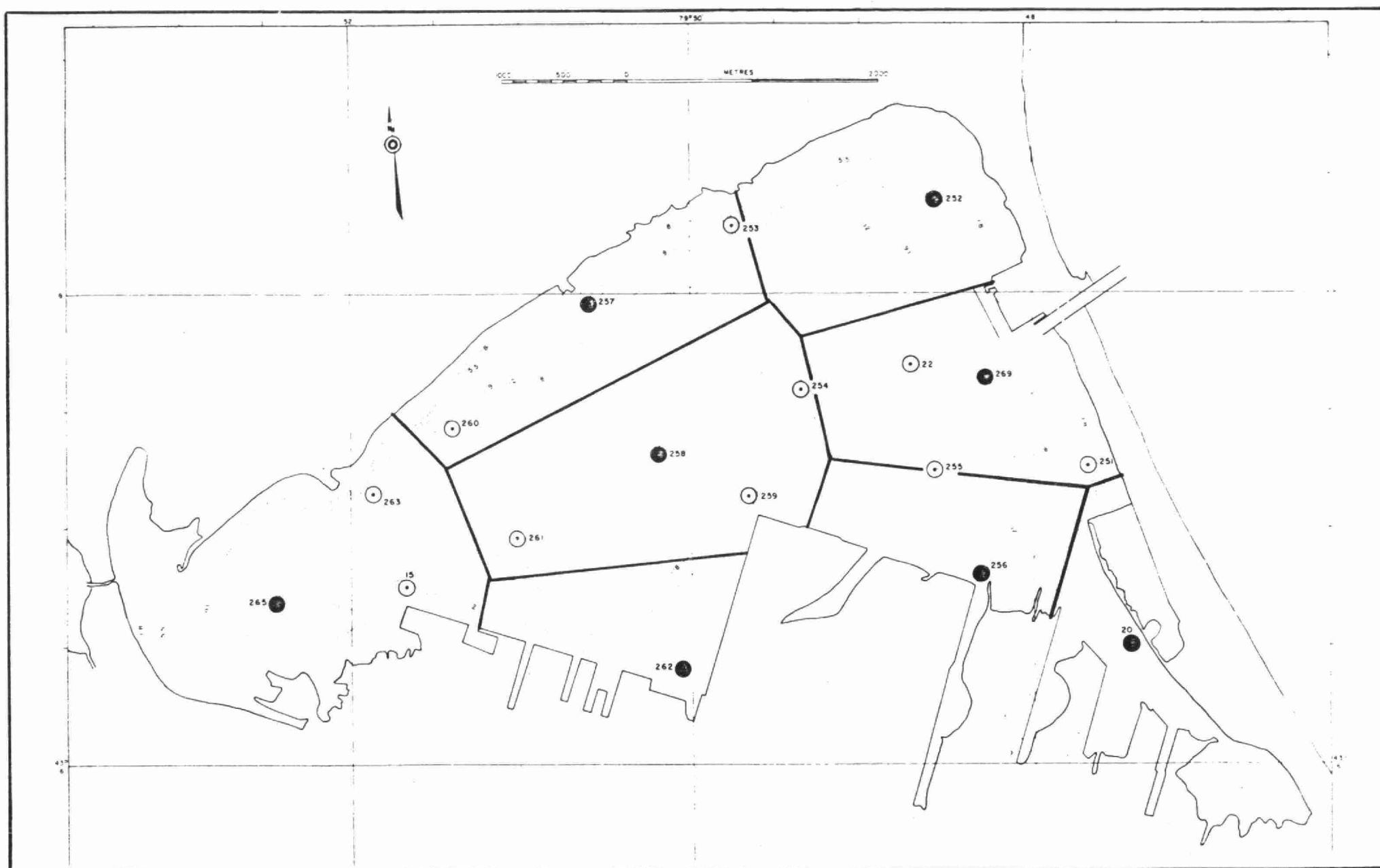
FIGURE I : REGIONS USED IN CALCULATING DISSOLVED OXYGEN STOCK, 8 STATION GRID

E-17
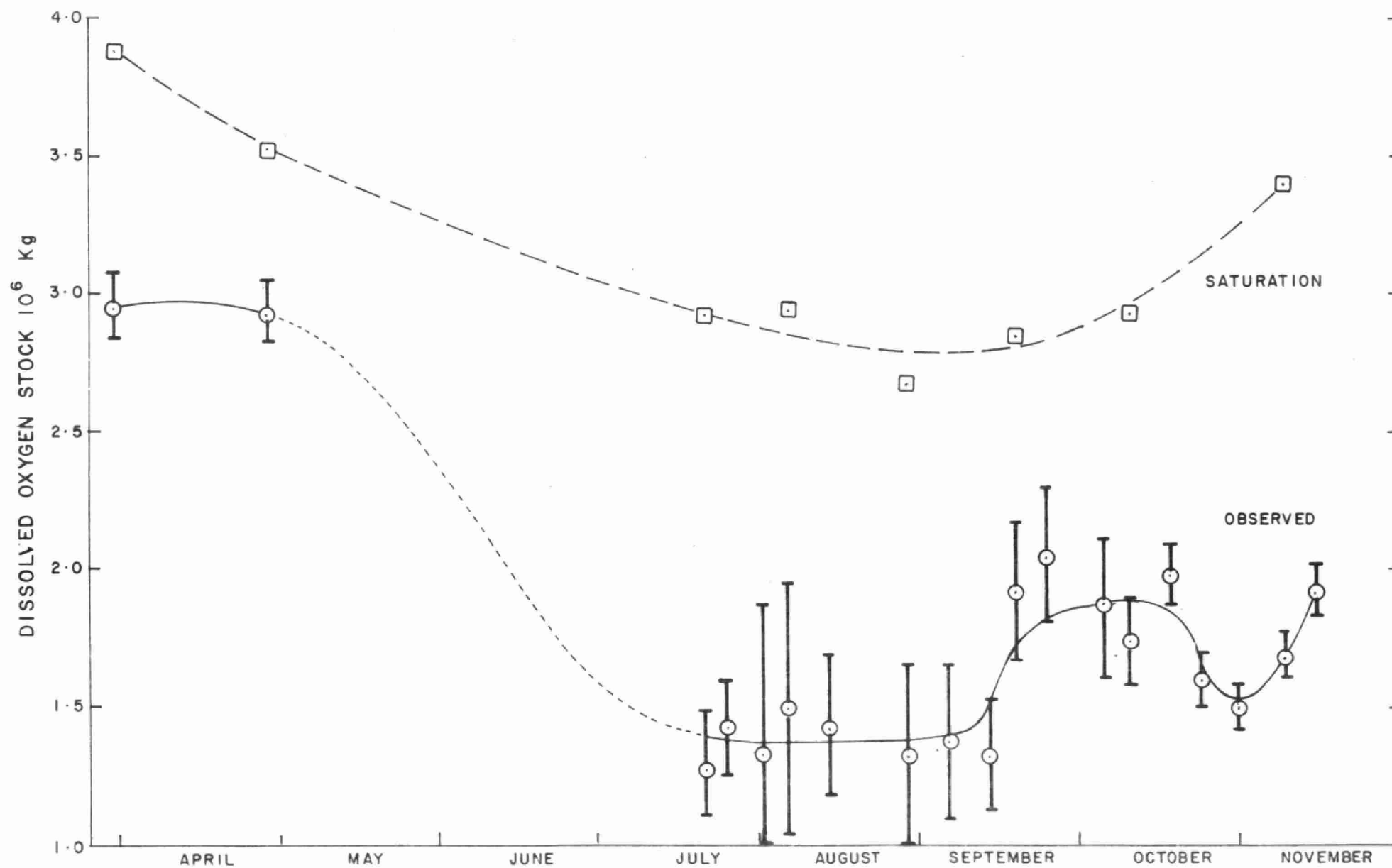
FIGURE : 2 OBSERVED AND SATURATION DISSOLVED OXYGEN STOCK IN HAMILTON HARBOUR, 1972

HAMILTON HARBOUR STUDY '74

section F

Phytoplankton

HAMILTON HARBOUR STUDY
SECTION F
THE PHYTOPLANKTON

SUMMARY

THE PHYTOPLANKTON OF HAMILTON HARBOUR WAS SURVEYED ON
SIX OCCASIONS DURING 1974. SIX SITES WERE SAMPLED
THROUGH THE EUPHOTIC ZONE. PHYTOPLANKTON WERE
IDENTIFIED TO GENERA, AND ENUMERATED TO DETERMINE
POPULATION COMPOSITION, ABUNDANCE AND DISTRIBUTION.
ALGAL POPULATIONS WERE LOW DESPITE HIGH NUTRIENT
LOADINGS. CYANOPHYCEAE WERE UNCOMMONLY SCARCE, AND
CHLOROPHYCEAE DOMINATED ALL SAMPLES. GENERA SUCH AS
EUGLENA AND PHACUS WHICH ARE COMMON TO POLLUTED
WATERS, AND OTHER GENERA SUCH AS CRYPTOMONAS AND
RHODOMONAS, INDICATIVE OF ORGANIC POLLUTION, WERE
ALWAYS PRESENT. DIATOMS WERE NOT ABUNDANT, DESPITE
THE FREQUENT OCCURRENCE OF STEPHANODISCUS. REASONS
FOR LOW PRODUCTION ARE DISCUSSED, AND POSSIBLE
EFFECTS OF ARTIFICIAL MIXING ARE PRESENTED. PHYTO-
PLANKTON PRODUCTION CONTRIBUTED LITTLE TO THE TOTAL
ORGANIC CONTENT OF THE HARBOUR WATERS.

HAMILTON HARBOUR

THE PHYTOPLANKTON

Despite intensive chemical surveys of Hamilton Harbour since
1972, there has been no complementary study of the phyto-
plankton. During 1974 six stations, numbers 20, 262, 256,
265, 254, and 253 were monitored for phytoplankton composi-
tion and abundance. Samples were collected by passing a 32
oz bottle through the euphotic zone. Euphotic depth was
considered to be twice the depth of the Secchi disc obser-
vation.

Phytoplankton were identified to genera and standing crop
determined in Areal Standard Units (one A.S.U. = 400 square
microns phytoplankton surface area). This is not an accept-
able measure of biomass, but does serve as a basis to deter-
mine relative changes in phytoplankton populations. Future
surveys should represent biomass as algal volume.

Only two stations (253 and 20) were monitored continuously
from June 25, 1974 to October 2, 1974. Because of the sampl-
ing routines and the method of enumeration, spatial distribu-
tions of phytoplankton in the harbour could not be determined.
Only relative temporal variations can be commented on, with
general comparisons between stations. Table 1 outlines the
phytoplankton standing crops in Hamilton Harbour. During
1974 station 253 tended to have the higher standing crops
reaching a maximum on August 21, of 3052 A.S.U. ($\approx$ 20 ug.ℓ.'
Chlorophyll - a). This is extremely low compared to chloro-
phyll - a levels exceeding 3.0×10^3 ug-l$^-$' recorded in
Cootes Paradise by Harris (1974). It is not known if the
standing crop at station 253 was the result of higher
production, or was an artifact of the mosaic of transport
mechanisms operating within the harbour.

Station 20 had low phytoplankton populations (see Table 1,
and Figure 1), but did reach a maximum of 3,200 A.S.U. in
June, 1974. Similar to the other stations, Chlorophyceaen
species dominated the algal component of the seston at this
site.

The highly eutrophic nature of the harbour is reflected in
the species composition of the phytoplankton. Genera such
as Euglena, Phacus, Cryptomonas, and Rhodomonas reflect the
high level of organic pollution in the harbour. The large
centric diatom Stephanodiscus is common in eutrophic bodies
of water and was present at all times of the year in the
harbour.

There was a conspicuous lack of blue-green algae (Cyano-
phyceae) in all samples. As Hamilton Harbour has a rela-
tively low pH (7.0 - 8.0) and relatively moderate alkalinity
(80 - 110 mg. l^{-1} as $CaCO_3$) there would be abundant CO_2 to
support both green and blue-green algae. The low production
of blue-green populations might be a response to the low
thermal stability of the water column in the harbour, as the
thermocline usually stays at about four metres depth despite
increasing radiant energy. This lack of stability is quite
likely a result of large horizontal flows throughout the
basin, and disturbance of the water column by shipping.
Many Cyanophyceae are adapted to stabilized water columns,
and the lack of such might limit their production. Genera
of the Chlorophyceae such as Scenedesmus, Coelastrum and
Oocystis are not adversely affected by low stability, and
demonstrate a growth potential in the harbour (see Figures
1,2 and 3).

The phytoplankton populations outlined in Table 1 are low
considering the hypertrophic nature of the harbour. Nutrient
levels in Hamilton Harbour (Section A; Table 1) suggest high
nitrate availability, but surprisingly low orthophosphate
levels. These phosphate results are spurious, as soluble
phosphate levels are near the minimum level for detection,
and increase directly with chlorophyll - a. If soluble
phosphate was limiting an inverse relationship would be
expected. Sample collections were not frequent enough to
comment on the phosphate - production dynamics of the harbour.

Compared with total organic carbon levels of previous years
(M.O.E., 1974), of 6.0 - 8.0 mg. l^{-1}, the phytoplankton com-
ponent is relatively small (1 mg. l^{-1}). It would appear
that much of the organic content of the harbour is from
waste discharge into the epilimnion. Possible effects of the
phytoplankton on the total dissolved oxygen budget (Section
E) are not known, as measurements of primary productivity
(light and dark bottle method) have not been made. It must
also be established if there were any localized growths
within the harbour, and a realistic determination of total
phytoplankton production made.

Zooplankton data is scarce, but net collections on June 25,
1974 suggested moderate zooplankton levels. The hauls were
just through the euphotic zone, and are not indicative of
the water column. It would appear that zooplankton popu-
lations were not sufficiently high to maintain such low
algal standing crops (Uhlmann, 1971). There is a cons-
picuous absence of Daphnia in all collections. Further
study is required to determine reasons for this absence, but
combined with low algal production, toxicity must not be
overlooked. A second possible limiting source is the
turbidity of the harbour waters. Secchi disc observations
indicate low transparency which must be a result of high

The vertical light attenuation coefficient of Hamilton Harbour is approximately 1.5, but submersible photocells are required for more accurate determinations. Such a high attenuation coefficient would suggest there is very limited photosynthetic available radiation penetrating the water column. This will severely limit phytoplankton production (see Section G on artificial mixing) in moderately deep water columns.

Artificial mixing of Hamilton Harbour could result in a change in the abundance and composition of the phytoplankton, and will in turn affect the zooplankton. Mixing can result in increased dissolved carbon dioxide in the euphotic zone, and combined with low stability of a mixed water column often results in a shift of bluegreen algae to green algae. Hamilton Harbour, however, is presently dominated by members of the Chlorophyceae. If there is a change in the algal composition it might well favour diatoms, and genera such as Stephanodiscus, Fragilaria, Asterionella, Melosira, and Cyclotella would increase in abundance as they are adapted to vertical mixing in deep water (see Lund, 1971).

It is not possible to predict the effects of mixing on the algae. Physical and chemical changes exert numerous in-direct effects on the plankton, and the response is to the summation of the effects. It is not unlikely that the abundance of green algae will drop if the turbidity of the harbour remains high, and the algal cells are mixed through the water column. The cells will not obtain sufficient photosynthetic energy to assimilate carbon under these circumstances. Figures 1,2, and 3 illustrate a decrease in phytoplankton abundance in the autumn of 1974. This is associated with the breaking down of thermal stratification and the resultant increase in the depth of vertical mixing. Production in Hamilton Harbour can be limited by the physical processes which influence the mixing depth.

During 1975 an intensive biological survey will be initiated. Phytoplankton composition, abundance and distribution will be determined. Primary production experiments will be set up, and bioassays used to assess the production potential of the harbour water. Relative abundance and composition of zooplankton and fish populations will be determined. This survey will include an investigation in changes of bottom fauna and bacterial populations as there is suitable back-ground data to determine the effects of mixing on these parameters.

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TABLE 1

Phytoplankton Abundance 1974

All Figures are in Areal Standard Units ml^{-1}

STATION

Date	20	262	256	265	254	253
June 25/74	3244	–	–	2930	2154	2375
July 5/74	1068	615	424	1297	2554	583
Aug. 8/74	1363	–	3319	1996	3394	2847
Aug. 21/74	1405	–	–	2050	1417	3052
Sept.25/74	1732	–	–	–	–	3041
Oct. 2/74	990	–	–	–	1029	1853
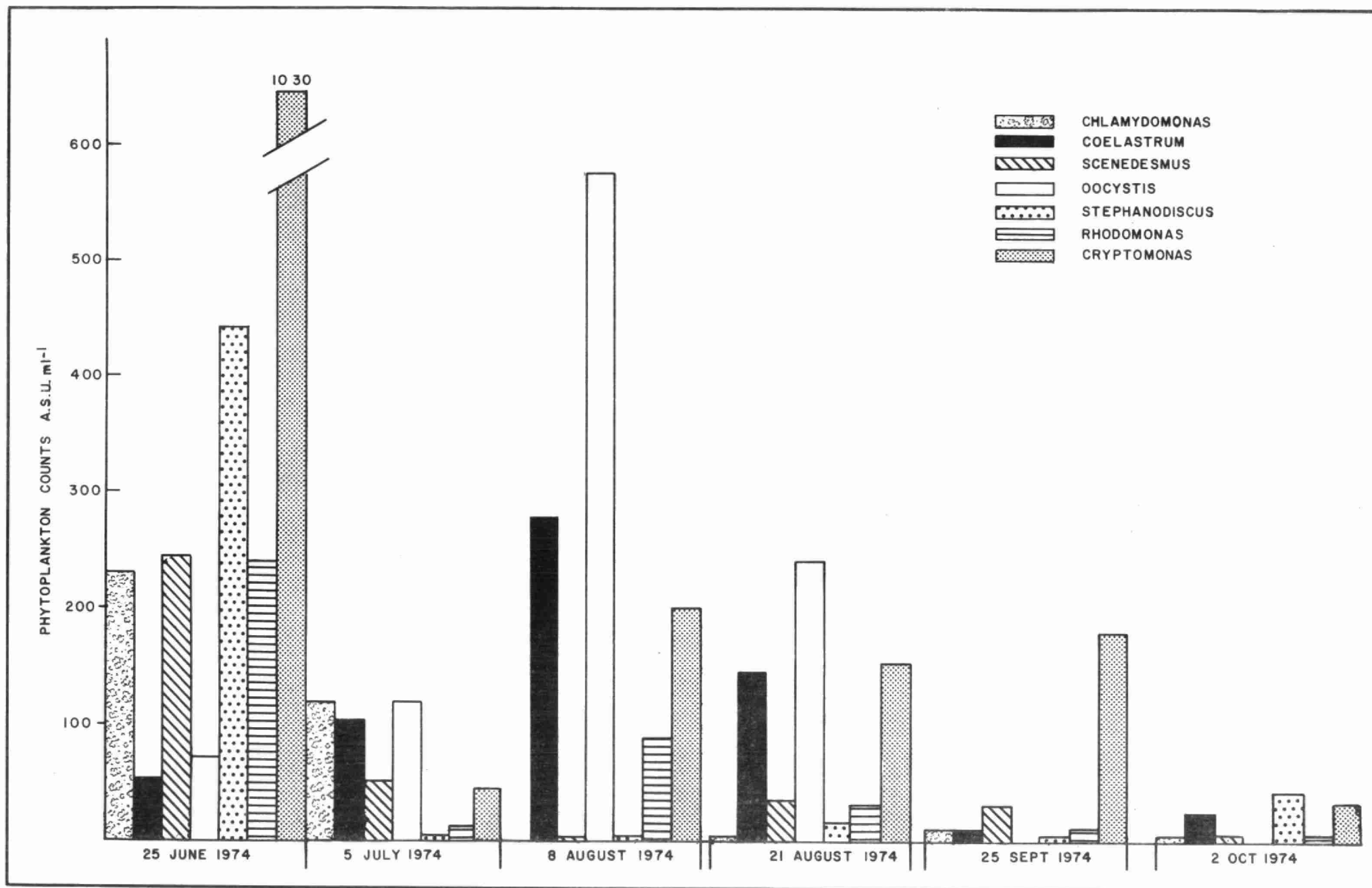
FIG. I SEASONAL VARIATION OF PHYTOPLANKTON IN HAMILTON HARBOUR 1974, (COMPOSITES OF EUPHOTIC ZONE, STATION 20).
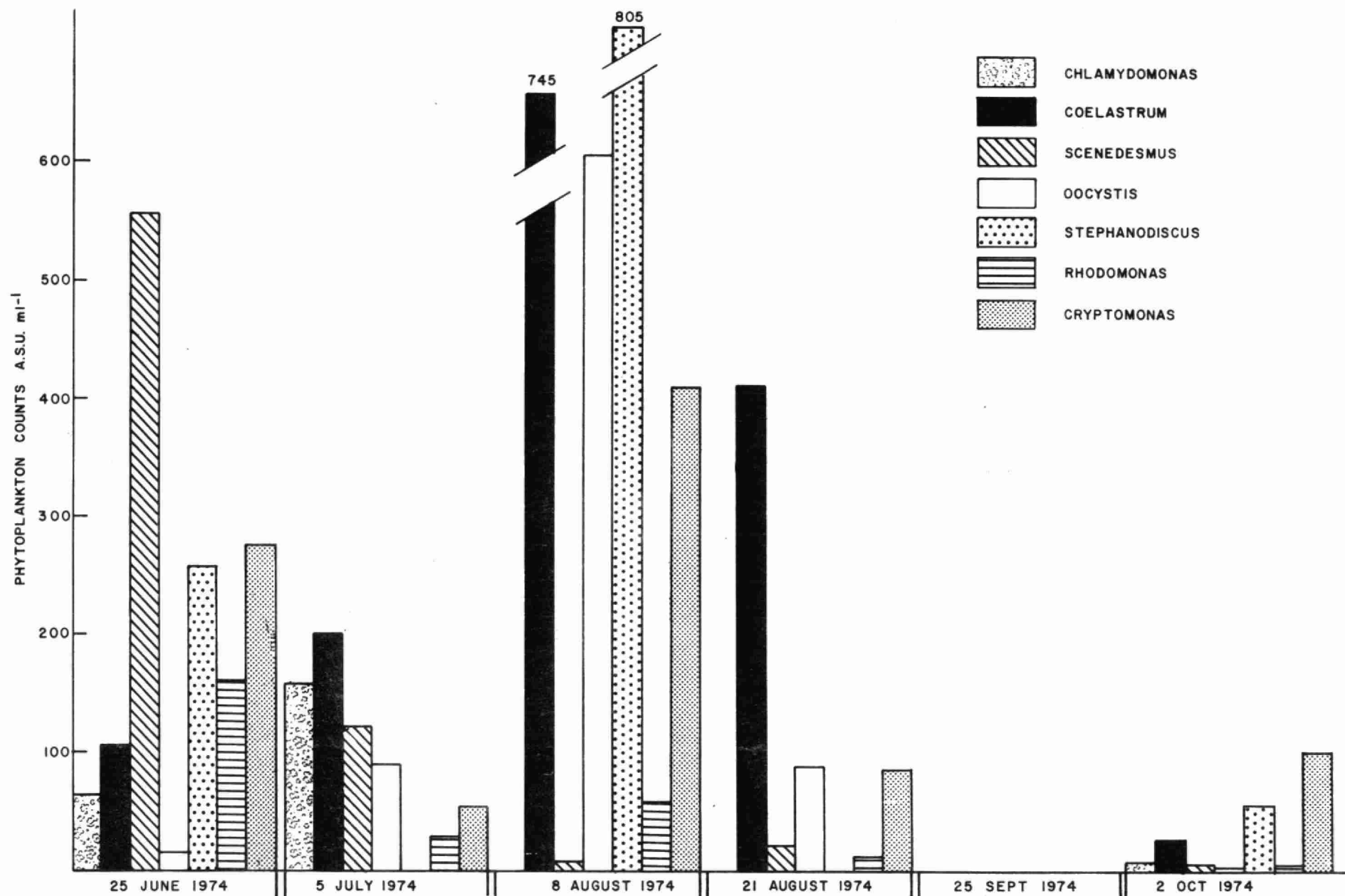
FIG. 2 SEASONAL VARIATION OF PHYTOPLANKTON IN HAMILTON HARBOUR 1974, (COMPOSITES OF EUPHOTIC ZONE, STATION 254).
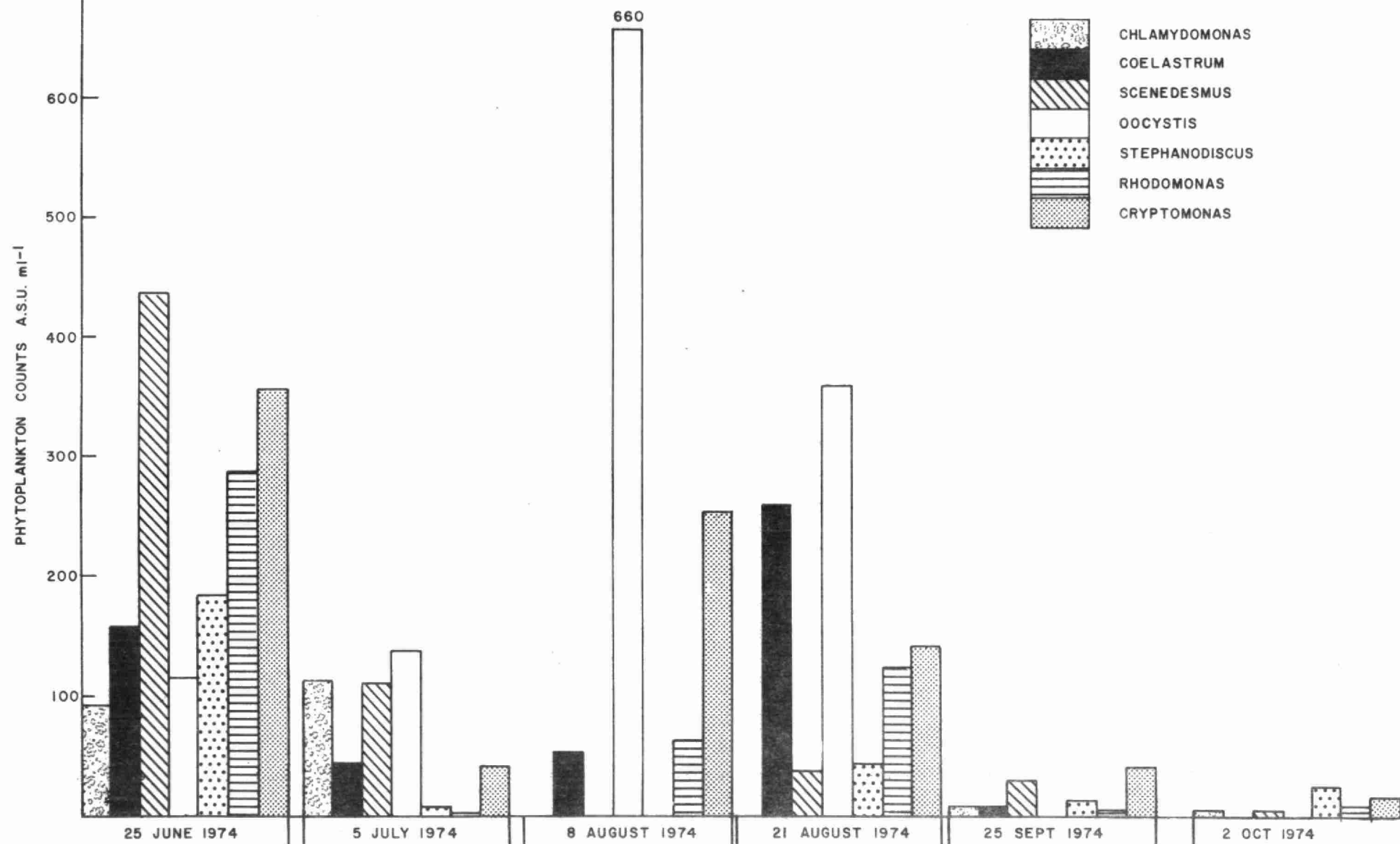
FIG.3 SEASONAL VARIATION OF PHYTOPLANKTON IN HAMILTON HARBOUR 1974, (COMPOSITES OF EUPHOTIC ZONE, STATION 253).

HAMILTON HARBOUR STUDY '74

section G

Artificial mixing

Artificial Mixing and Water

Quality in Hamilton Harbour

Introduction

Artificial mixing has been used to improve water quality and
manage biological production in aquatic systems. Anoxic
conditions, such as the hypolimnetic depletion of oxygen in
Hamilton Harbour, can be ameliorated by the correct mixing
process. Various methods of mixing are common (Fast, 1968).
The most frequently used and most economical form of mixing
is aeration. This technique is often applied to situations
of low oxygen levels (Imhoff, 1969; Patriarche, 1961) to
restore dissolved oxygen to the system. Mechanical pumping
of water is a more expensive alternative to aeration, but
does increase the effective exchange area of the water-air
interface.

Hooper, Ball and Tanner (1952) were the first to report the
use of artificial mixing in North America. Complete destra-
tification was not achieved by the mechanical pumping of
hypolimnetic water into the epilimnion, but phytoplankton
production was stimulated.

Reasons for implementing artificial mixing vary according to
water use (EPA, 1973). Impoundments for freshwater supply
use artificial mixing to prevent hypolimnetic anoxia, thereby
increasing the volume of potable water (Ridley, Cooley and
Steel, 1966; Ridley, 1964; Ridley, 1970). Natural lakes are
mixed to prevent winterkill of fish (Burdick, 1959; Halsey,
1968; Schmitz and Hasler, 1958), but not always successfully
(Patriarche, 1961). Yount (1966) failed to reduce the
levels of nutrients in hypertrophic lakes in Florida by
aeration, possibly as a result of a poorly established
oxidized microzone at the mud-water interface. Improvement
of polluted lakes by aeration has been reported (Heath,
1961), but in most cases mixing is used as a management
process, not as a corrective or lake renewal mechanism.
There is little known work on the effects of mixing on
bodies of water which have large industrial discharges and
intakes. High COD's are usually treated before discharge in
many circumstances, and artificial mixing would not be as
effective as pretreatment processes.

Artificial mixing is often used to prevent or destroy thermal
stratification. Independent mixing of the epilmnion (Bernhardt,
1967) or the hypolimnion (Speece, 1970) is possible, but is
used in isolated circumstances as a result of inefficient
mixing techniques or high costs (see Dunst, 1974). Hypolim-
netic aeration has a promising future should appropriate
methods be found.

A major review of the principles and techniques of artificial mixing has been made by Fast (1968). Symons (1969) compiled an extensive list of references on the use and efficiency of vertical artificial circulation in lakes and reservoirs. The American Water Works Association (1970) reviewed the results of artificially induced circulation, and noted that 90% of mixing trials were considered successful. A review of mixing comparing depth, area and volume of lakes with types of mixing and problems encountered is appended at the end of this section.

Results of Artificial Destratification

General improvements in water quality associated with artificial mixing are:

1. Elimination of taste, odour and colour (A.W.W.A. 1970)

2. Improved transparency. (A.W.W.A. 1970)

3. Larger habitat for aquatic life. (Inland Fisheries Branch, 1970).

4. Increased dissolved oxygen. (Posey and De Witt, 1970; Imhoff, 1969).

5. Reduced algal blooms but not necessarily implying reduced algal production. (Bernhardt, 1967; Symons, Carswell, and Robeck, 1969; Bakus, 1973).

6. More neutral pH, as CO_2 is released from hypolimnion. (Riddick, 1957; see, however, Lackey, 1972).

7. Decrease in dissolved metal content, especially Fe and Mn. (Symons, Carswell and Robeck, 1969; see, however, Lackey, 1972).

Chemical Results

Chemical effects of artificial circulation are dependent on the efficiency of the mixing process (Pasveer, 1965; Symons and Robeck, 1969). Inverse clinograde distributions of Fe, Mn, $N-NH_3$, CO_2, alkalinity and conductivity associated with a discontinuous temperature profile can be corrected.

Iron and manganese precipitate out as hydroxides in aerobic conditions assuming the pH is sufficiently high. The maintenance of an oxidized microzone will prevent recycling of these metals and their salts, iron phosphate complexes in particular (Ontario Ministry of the Environment, 1974).

A possible deleterious point of artificial mixing is a general increase in total phosphates as a result of disturbance of the lake floor. Associated with this problem are decreased sinking rates of organic and inorganic particles, and extended periods of high turbidity.

The development of an oxidized microzone at the sediment-water interface is an essential feature of successful artificial mixing. This microzone might satisfy some surface sediment oxygen demand, but does not necessarily affect the oxygen demand of sediments as determined by laboratory analyses, and by the requirement of at least intermittent mixing to maintain aerobic conditions. This microzone retards the recycling of nutrients (Mortimer, 1941; 1942; 1971), and the sediment will act as a nutrient sink (see, however, Tessenow, 1964, 1966), with a gradual build up of reduced material below the microzone. There is little evidence that artificial mixing ever satiates the sediment oxygen demand.

Biological Results

Changes in bacterial populations as a result of artificial circulation are difficult to determine, and little work has been done in this field. Anaerobic decomposition of organic matter releases NH_3-N as an end product. A second source of ammonia is the reduction of nitrate by bacteria, and hence ammonia tends to accumulate in the hypolimnion. Anaerobic decomposition is slow, and often results in an accumulation of organic material in and above the sediment. Artificial mixing should favor the presence of nitrifying and heterotrophic bacteria, resulting in increased decomposition of organic matter, particularily at the sediment-water interface, and a decline in the level of ammonia. There is a possibility of the accumulation of nitrates as a consequence of continued artificial mixing.

Dissolved carbon dioxide and alkalinity are to a large extent interdependent on the pH and plant communities of the lake. CO_2 tends to accumulate in the hypolimnion of a stabilized water column. Artificial mixing can produce an orthograde ratio of CO_2/alkalinity interdependent on pH. Changes in the available carbon associated with mixing can result in a significant response in phytoplankton growth and succession. Composition of the standing crop might be altered, as King (1970) noted that high levels of dissolved carbon dioxide favored green flagellates. Blue-green algae can utilize low CO_2 levels (common in an epilimnion) hence low carbon dioxide regimes tend to favor their growth in the euphotic zone. Mixing tends to increase the available carbon dioxide in the euphotic zone, and green algae are favoured. This, however, is a broad generalization, and in reality many other factors such as temperature, vertical attenuation and modification of radiant energy, and mixing

depth can have an equal or greater effect on the phyto-
plankton response. Hamilton Harbour is already dominated by
green algae, probably as a result of the cumulative effect
of all these factors.

The composition, periodicity, duration and size of phyto-
plankton standing crop can be altered by the mixing process.
Phytoplankton populations are often interactive and inter-
dependent on the physical-chemical parameters which are
affected by artificial mixing. These indirect effects of
mixing, coupled with the direct effects of mixing on cells
(vertically homogeneous algal populations), produce short
and long term effects on the populations. Because of the
complexity of the interactions, reservations must be made
when predicting the effects of mixing on phytoplankton and
zooplankton production and distribution (Talling, 1970;
Fast, 1971). These in turn can combine with the physical-
chemical changes and affect bottom fauna and fish populations
(Murphy, 1962).

While preventing the growth of species adapted to stabilized
water columns, such as many species of Cyanophyceae, artifi-
cial destratification can stimulate the growth of other
algae. Green algae (Chlorophyceae) can dominate when eutro-
phic bodies of water are mixed, especially if the water
column is optically shallow. A water column is optically
shallow when the mixing depth (Zm) and the euphotic depth
(Zεu) are similar.

Diatoms might dominate if the mixed water column is optically
deep (Zm >> Z eu), and other physical-chemical features are
favourable.

Lund (1954, 1955, 1971) has noted that mixing can alter the
seasonality and size of populations of Melosira islandica
(Ehrenb) Kutz. subsp. subarctica O. Mull. in the English
Lake District. Ridley (1970) reported delays in the vernal
maxima of Stephanodiscus astraea (Ehrenb) Grun. which were
possibly related to prolonged turbidity caused by artificial
mixing.

Haynes (1973) found mixing resulted in a decrease of
Aphanizomenon flos aquae Ralfs., and Steel (1972) noted that
vernal growths of phytoplankton in Thames Valley Reservoirs
were inversely related to the mixing depth and vertical
light attenuation.

Phytoplankton Productivity

Phytoplankton production per unit area in m^2 can be formulated
as:

$$n \int_0^z P_z \, dz = \frac{n \, P_{max}}{\sigma \, \varepsilon_{min}} \left\{ Sinh^{-1} \frac{I_o}{I_k} - Sinh^{-1} \left(\frac{I_o e^{-\sigma \varepsilon_{min} Z_m}}{I_k} \right) \right\}$$

where

n = algal concentration (mg chlorophyll $\underline{a}$ m^{-3}).

P_{max} = maximum photosynthetic rate

$\sigma \, \varepsilon_{min}$ = vertical attenuation coefficient of photosynthetic available radiation (m^{-1}). σ is a correction for spectral modification with depth.

I_o = incident radiation (K ergs cm^{-2} sec^{-1})

I_k = light intensity at onset of photosynthetic light saturatio (K ergs cm^{-2} sec^{-1})

Z_m = depth of mixed water column (m)

Such a model (Steel, 1972) of the energy flows associated with phytoplankton populations is advantageous when eutrophic bodies of water are mixed. When $\sigma \, \varepsilon_{min} \, Z_m$ is great,

$$\left(\frac{I_o \, e^{-\sigma \, \varepsilon_{min} \, Z_m}}{I_k} \right)$$

will tend to zero, and the photosynthetic profile will be contained within the mixed water column. Such a body of water is optically deep ($Z_m \gg Z \, eu$). Scotch Block Reservoir and Buchanan Lake are optically deep (see Appendix 1, No.14 and 16) bodies of water destratified by the Ministry of the Environment. Valens Reservoir, also artificially mixed, is optically shallow with light penetration near or to the bottom.

As Hamilton Harbour is classified as eutrophic-hypertrophic, and is optically deep, it is expected that primary production will be limited by available solar radiation. Despite the fact that the volume of water which will support aquatic life will probably be increased by artificial mixing, the actual biological production of the harbour will not necessarily increase.

Expected Results Hamilton Harbour

The main goal of the destratification of Hamilton Harbour is to relieve the anoxic conditions in the hypolimnion. It is hoped that this will result in better water quality, although chemical and biological responses are impossible to predict at this time. The irregular shape and depth of the harbour, the nature of the mud-water interface and the geographical environment of the harbour are some of the many unknown factors which will influence the response of the harbour to artificial mixing. Horizontal transport processes in the harbour are relatively large (M.O.E., 1974) and should assist the mixing process, but would not necessarily ensure aerobic conditions at the microzone without the assistance of an aerator. Locating the aerator at the deepest point will help maintain the oxidized microzone throughout the harbour. An agency mixing effect of the wind might compensate for the irregularities in the shape of the harbour. Considering the mixing depth of Hamilton Harbour (> 20m), and that the water is optically deep, it is expected that the phytoplankton composition might shift towards species adapted to low light and mixing conditions. Many diatoms are adapted to such conditions, and it is possible there will be an increase in diatom populations in the harbour waters.

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APPENDIX I

A Compilation of References and Results
on Artificial Mixing and Reaeration

Reference	Methods	Results
(1) Wiley, A.J., Lueck, B.F., Scott, R.H., and Wisniewski, T. F. 1962. Commercial-scale stream reaeration J. Wat. Pollution Control Fed. 34 (4): 401-411.	Turbines equipped with reaeration plates, installed on dams. No specifications given.	Hydroturbine aeration is approximately 25% efficient. It can increase the dissolved oxygen of a moving stream 900 Kg. of oxygen day^{-1}, 28 m^3 sec^{-1}.
(2) Posey, F.H. and DeWitt, J. W. 1970. Effects of reservoir impoundment on water quality. Proc. Amer. Soc. Civ. Eng. 96: 173-185.	(A) Reaeration of discharge by: 1) multilevel penstock intakes 2) submerged weirs 3) supplemental high quality spills 4) turbine aeration (B) Destratification by: 1) air hydraulic guns 2) perforated air tubing 3) mechanical pumps 4) diffused-air-pumping Allatoona Reservoir 4.5 x 10^{8}m^3 mixed by five cross-shaped air diffusers. Compressors (5) supply 250 cfm at 100 psi (7m^3 min^{-1} at 7 Kg.cm^{-2}).	(A) Turbine aeration successful. (B) Diffused air destratified Allatoona Reservoir.

Reference	Methods	Results

(3) Symons, J.M. Carswell, J.K., and Robeck, G.G. 1969 Mixing of water supply reservoirs for quality control. J. Amer. Water Works Ass. 61: 322-344.	Destratify two lakes by diffused air. Boltz Lake*:
	    19 m. (max. depth)
	    $3.9 \times 10^2 m^2$ (area)
	    $3.6 \times 10^6 m^3$ (vol.)
	
	Falmouth Lake
	    13 m. (max. depth)
	    $9.1 \times 10^5 m^2$ (area)
	    $5.7 \times 10^6 m^3$ (vol).
	
	Both lakes mixed by compressers operating at $3.2 m^3 \ min^{-1}$.
	
	*Mechanical pumping trial used for a limited period.
		Reduction of levels of Fe, Mn, SO_2 occurred, accompanied with a temporary decrease in phytoplankton populations. It was also noted that quality control should begin before any quality deterioration.

(4) Speece, E.R. 1970. Hypolimnion aeration. J. Amer. Water Works Ass. 72: 6-9.	Artificially induced aeration of the hypolimnion using a 2m diameter pipe. Alternative methods are discussed. The hypolimnion of Lake Bret was aerated by forcing water up the pipe and discharging it through laterial parts which were below the thermocline.	Advantages of hypolimnetic aeration are:
		    (1) temperature budget is not increased.
		    (2) still maintain oxidized microzone.
		    (3) cold water fish propogation.
		
		The dissolved oxygen of the hypolimnion can be increased from 5mg. l^{-1} to 10 mg. l^{-1}.

Reference	Methods	Results

(5) Imhoff, K.R. 1969. Oxygen balance and artificial re-aeration of Lake Baldeney and the lower Ruhr.
Advances in Water Pollution Research. Proc. 4th Internat. Conf. Prague. Pergamon Press. 761-774.
	Lake Baldeney
	  10m (max. depth)
	  $2.6 \times 10^3 m^2$ (area)
	  $9 \times 10^6 m^3$ (vol.)
	was reaerated using various methods in-cluding, a floating aerator, compressed air aeration system, floating aerator, and turbine aeration.
		More feasible to apply artificial reaeration than to increase re-moval rates of sewage plants be-yond 85% or to apply tertiary treatment.

(6) Symons, J.M., Irwin,W.H., Robinson, E.L. and Robeck, G.G. 1967. Impoundment destratification for raw water quality control using either mechanical or diffused air pumping. J. Amer. Water Works Ass. 59 (10): 1268-1291.	Same lakes as in reference 3. Boltz Lake mixed at 19m depth. Sixteen diffusers arranged in a cross pattern as before. A $1.6 \times 10^4 m^3$ day^{-1} mixed-flow pump was stationed at the deepest part of the lake permitting water drawn from the bottom be discharged at the surface.	Destratification is more effi-ciently achieved by aeration, as high discharge velocity head and hydraulic losses reduce efficiency of mechanical mixing. Blue green algal populations replaced by green, with a decline in total standing crop.

Reference	Methods	Results
(7) Patriarche, M.H. 1961. Air induced circulation of two shallow Michigan Lakes. J. Wildlife Management. 25 (3): 282-289.	Aeration with 150m perforated tubing attached to $0.14m^3 min^{-1}$ compressor. Two shallow lakes 2m and 1.5m depth, with areas of $2.9 \times 10^5 m^2$ and $6.8 \times 10^4 m^2$ respectively were mixed.	Depletion of dissolved oxygen causing winter kill of fish was not ameliorated. Large demand for oxygen by decay processes in the rich organic sediments was too great to be satiated by mixing. Artificial mixing resulted in large phytoplankton growths.
(8) Ridley, J.E., Cooley, P. and Steel, J.A. 1966. Control of thermal stratification in Thames Valley Reservoirs. Proc. Soc. Wat. Treat. Exam. 15: 225-244.	Large reservoirs* $18-25 \times 10^6 m^3$ mixed by jet-type inflow, or hydraulic pump located on pontoon. Jet type inflow $(4.5 \times 10^5 - 9.0 \times 10^5 m^3 day^{-1})$ or hydraulic pumping $(1.8 \times 10^5 m^3 day^{-1})$ achieved adequate mixing. *A reservoir of $3.5 \times 10^7 m^3$ was also mixed by jet-type inflow in 1972, (author's note).	Improved biochemical quality, but reservations expressed concerning phytoplankton production and distribution. Increased volume of water available for domestic uses. Jet inflow allows directional mixing within the basin.

Reference	Methods	Results
(9) Lackey, R.T. 1972. Responses of physical and chemical parameters to eliminating thermal stratification in a reservoir. Water Resources Bulletin 8 (3): 589-599.	Parvin Lake Reservoir (max. depth 10m, area = $4.0 \times 10^3 m^2$) was mixed by two aerators supplied by $2.1 m^3 min^{-1}$ compressor at 4.2 Kg m^{-2}.	Change in heat budget of the Lake. Alkalinity, pH, conductivity, and total Fe, Mn, were not significantly affected. Ca^{++} increases slightly, and SO_4^{-2} decreases.
(10) Bernhardt, H. 1967. Aeration of Wahnbach Reservoir without changing the temperature profile. J. Amer. Water Works Ass. 69: 943-964.	Wahnbach reservoir is 19m deep, with a volume of $4.16 \times 10^7 m$. Mixed with one to three aerators operating at 2, 4, and 6 $m^3 min^{-1}$ with a 36.5 Kw electrical compressor. Aerator designed such that water flows through a 2m diameter pipe, with lateral discharge apertures.	Until complete destratification was achieved with two aerators, Mn increased in concentration after full circulation Mn decreased, biological production remained unaffected. Also used mixing to lower thermocline but noticed that O_2 demand was still high even after complete circulation.

Reference	Methods	Results
(11) Roeber, J.A., Nogaj, R.J., Ciabattari, E.J. and Hurwitz, E. 1965. Floating aerator. Water Works and Wastes Engineering. 2: 64-66.	Stream aeration of a shallow river (1 metre). Aerator was designed to lift water above the general water level and spread the water across the surface. It was estimated that 8.2×10^3 Kg oxygen per day would be required using $40m^3$ of air per 0.454Kg of O_2. This experiment would require 10,000 hp for compression, but aerator was only 100 hp.	Efficiency of aeration depends on oxygen tensions existing in the water. Energy efficiencies varied from .3 Kg to 1.1 Kg of oxygen per hp hr.
(12) Biederman W.J. and Fulton, E.E. 1971. Destratification using air. J. Amer. Water Works Ass. 63: 462-467.	Waco Reservoir has a volume $1.28 \times 10^8 m^3$ with a maximum depth of 26m. A gasoline-powered compressor 25 hp delivering $3m^3 \, min^{-1}$ of air was used to destratify the reservoir. Replaced plastic delivery line with galvanized pipe as a result of breakage problems. Diffuser was 15m of galvanized pipe with $\approx$ 3mm holes.	Solved taste and odour problems associated with stratification No algal blooms were reported.

Reference	Methods	Results
(13) Haynes, R.C. 1973. Some ecological effects of artificial circulation on a small eutrophic lake with particular emphasis on phytoplankton. Hydrobiologia, 43: 463-504.	Kezar Lake is a small lake, 9m max. depth, with a volume of $2.0 \times 10^6 m^3$. Four compressors of 3 hp each, collectively discharged air at $3m^3min^{-1}$. P.V.C. delivery line terminated at a junction of four arms each with 3 ceramic diffusers.	A noxious blue green alga was replaced by chlorophycean species. Ca, Mg, K, Cl, SiO_2 were not affected. Increase in Total PO_4 associated with increased suspended material.
(14) Ontario Water Resources Commission, 1971. A.I.D. for lakes program. Artificially induced destratification. Toronto, Ontario.	A 2 hp compressor deliverying $0.3m^3min^{-1}$ of air was used to destratify a lake with maximum depth of 13.4m, area of $8.6 \times 10^4 m^2$, and volume of $4.3 \times 10^5 m^3$. Turnover time was 4.8 hrs, and vertical velocity due to air is 30 cm/sec^{-1}.	Increased production of phyto-and zooplankton. Improved water quality in regard to levels of H_2S, CO_2, NH_3, and Fe. Marginal improvement in bottom fauna and sediment chemistry.

Reference	Methods	Results
(15) Ontario Ministry of the Environment. 1972. Artificially induced destratification of Valens Lake. Toronto. 33pp.	A 2hp compressor delivering $0.28m^3min^{-1}$ destratified a lake 4.0m deep, $4.9x10^5m^2$ area, $1.2x10^6m^3$ volume using six diffusers of 6 metres length with 20 holes in each. Velocity of water due to air $\sim$ 8.5-12.0 cm sec^{-1}.	Iron and hardness of the water decreased. Dissolved oxygen improved in area of the diffuser. Odour problems (H_2S) were improved, and an extremely high density of macroinvertebrates were noted.
(16) Ministry of the Environment, 1973. Artificial destratification of Scotch Block Reservoir. A progress report in the changes in water chemistry through the period May to November, 1973. Toronto.	Scotch Block Reservoir ($1.8x10^6m^3$ with an area of $5.3x10^5m^2$) is $\sim$ 15m deep. The reservoir was mixed by a 5hp compressor delivering air at a rate of $0.56m^3min^{-1}$. Fifteen metres of neoprene pipe connected the aerator-delivery line system. Aerator sections (6m length with ten 1.5mm apertures) were alternated with delivery sections of 30m length. Six aerators were used.	Reduced downstream impairment which had resulted from stratification in the reservoir. Evidence of an excessive O_2 demand by the sediment, which resulted in no appreciable increase in dissolved oxygen content of the bottom waters. Controlled levels of H_2S, NH_3 and CO_2.
(17) Eunpu, F.F. 1973 Control of reservoir eutrophication. J. Amer. Water Works Ass. 65 (4): 268-274.	Occoquan Reservoir extends over $6.9x10^6m^2$ with a volume of $3.7x10^8m^3$. Three rotary compressors with a total capacity of $6.3m^3min^{-1}$ were attached to $2.3x10^3m$ of perforated tubing, which was fed by $7.6x10^3m$ of supply tubing.	Reduction of H_2S and elimination of anaerobic conditions. Reservoir was isothermal with no algal blooms since artificial mixing initiated.

HAMILTON HARBOUR STUDY '74

section H

Extracts from May 1974 report

HAMILTON HARBOUR

DESCRIPTION OF HARBOUR

Hamilton Harbour is an enclosed body of fresh water at the
western end of Lake Ontario approximately 8 km (5 miles) in
the east-west direction with 4.8 km (3 miles) in the north-
south direction. It is connected by a ships' canal, 732 m
(2400 ft) long by 107 m (350 ft) wide and 9 m (30 ft) deep
to Lake Ontario. The harbour contains approximately 2.8 x
10^8 m^3 (9.9 x 10^9 ft^3) of water with a mean depth of 13 m
(43 ft). Hamilton Harbour receives drainage from a water-
shed of 500 km^2 (190 mi^2) through several small creeks which
drain into the harbour with a total annual flow of 1.27 x
10^8 m^3 (2.8 x 10^4 MIG) consequently, the natural throughput
is approximately 45 percent per year.

The industries located on the highly developed south shore
use 27 m^3/sec (510 MIGD) water as an industrial supply,
returning a similar amount of effluent to the harbour. They
also depend upon the harbour for shipping of raw materials
and finished products.

Municipal utilities also use the harbour as a receiving
water for 3.2 m^3/sec (61 MIGD) of treated wastes and for
untreated storm sewer overflows estimated at 0.1 m^3/sec (1.9
MIGD) during overflow periods. Together with the natural
flow, this results in a total annual flow of 2.3 x 10^8 m^3,
or a throughput of approximately 80 percent per year.
Presently, the harbour is also used for recreational boating.

As the harbour shoreline is extensively developed; the
industries, Hamilton Harbour Commissioners and private
developers have adopted landfilling as a technique for
acquiring new land for expansion for many years. Concern
has been voiced that the landfilling has also become the
object of public concern lest the water quality of the
harbour be degraded. Both industry and the municipalities
recognize the importance of the harbour water quality and
have installed treatment facilities. While it is unlikely
that the water quality in the harbour regions directly
adjacent to the industrial shoreline can be brought to a
level which meets the criteria for fish, wildlife and
recreation, these criteria could be achieved in the remain-
ing portions of the harbour.

PURPOSE OF THE STUDY

In 1972, the Ontario Ministry of the Environment undertook a
water quality study of the harbour. The objectives of the
study were: to determine existing water quality and its
trends over recent years; to identify problems and recommend

corrective measures; and to determine the effects of land-filling on water quality. The water quality in the harbour is a result of the interactions of biological, chemical and physical processes in what was found to be a very dynamic environmental system. Thus, changes in any one process will affect the harbour water quality; consequently, it is necessary to understand the processes and their interactions in sufficient detail if intelligent decisions are to be made.

OUTLINE OF STUDY

Extensive water quality surveys were carried out during 1972 and 1973. Various components of the harbour processes were examined using the survey data as a base. The study of each of these components formed the subject matter of a technical bulletin. A draft of these reports was reviewed by Ministry personnel and subsequently amended incorporating their comments.

Each of these bulletins appears as a separate section of this report. Some duplication of figures and tables obviously results, but this is necessary if the sections are to be self-contained. The sections are as follows:

A. Harbour Periodicities
B. Nutrient Trend Analysis
C. Iron-Phosphate Relationships
D. Dissolved Oxygen
E. Numerical Model
F. Bottom Fauna and Bacteriology
H. Survey Data

In this preface, the results of the study are summarized and merged to provide comprehensive statements concerning the water quality as related to the purposes of the study.

Several sources were used in the collection of the water quality data which form the basis of this report. Water and bottom sediment samples were obtained by conventional grab sampling techniques. Recording instrumentation (wind, water quality and current) was used to obtain time histories of physical properties and water quality. Bottom fauna samples and fish were collected. Historical water quality data were obtained from surveys conducted by the Hamilton Municipal Laboratories and the Ontario Water Resources Commission.

SUMMARY AND FINDINGS

Trophic State

The hypertrophic state (mean annual chlorophyll $\underline{a}$ 20 ug/l and total phosphorus 40 to 200 ug/l) of the harbour fails to

meet the provincial objectives for fish and wildlife or
aesthetics and recreation. Annual nitrogen and phosphorus
loadings are five and thirty times the stock of these
nutrients in the harbour respectively, indicating the
importance of chemical and biological removal in preventing
increases in their concentrations. An analysis of the iron-
phosphorus relationships in the harbour indicates that
phosphorus removal will not cause significant increases in
the iron concentrations. Total phosphorus and ammonia
concentrations in the epilimnion during stratification are
significantly higher than those in the hypolimnion, indi-
cating that destratification would be beneficial.

Dissolved Oxygen

Dissolved oxygen levels below 5 mg/l exist in the lower
portion of the hypolimnion for large regions of the harbour
from July to September except during high wind conditions.
These portions of the harbour do not meet the provincial
criteria of greater than 5 mg/l for the protection of fish
and wildlife. The areas in the deep portion, near the
Hamilton WPCP, along the industrial south shore and at the
western end have the largest oxygen deficits. It is esti-
mated that approximately 66 percent of the deficit is caused
by discharges and sediment demand and 33 percent by phytoplankton
decay in August. A reduction in chemical oxygen demand
loadings of approximately 66 percent will result in a
reduction in deficit by about 5 percent in the first year.
The sediment demand should be controlled by nutrient concen-
tration reductions, oxidation and possibly selected sediment
removal.

Landfilling

Landfilling is causing a measurable degradation of water
quality in the region of the filling. Regions of the
harbour adjacent to the outfalls will experience higher
concentrations although only a very small portion will
exceed the 33 percent increase limit defined as an objective
for fish and wildlife. This problem can be relieved by
ceasing to fill, improving treatment at the principal
discharges and/or utilizing more harbour water for assimi-
lation through the use of destratification.

Microbiology

Bacterial levels of coliforms, fecal coliforms and entero-
cocci are generally higher than permitted for recreational
waters. If this use is contemplated the sources of con-
tamination must be determined and corrected. The storm
water sewers are a likely source, however, it was not
possible to correlate rainfall with higher concentrations of

total phosphorus or nitrate during the 1972 surveys. (These chemical parameters are normally the most sensitive in urban areasand have been useful in other studies in identifying storm water overflows or bypasses.) It is considered that other sources are also contributing to bacterial contamination like industrial discharges or wildlife. No changes in bacterial levels was observed in the period 1970 to 1972.

Bottom Fauna

The surveys in 1972 and 1973 indicate a slight improvement in bottom fauna species in density and diversity from the 1964-65 survey. This may be related to reductions in ammonia concentrations. However, the region devoid of macroinvertebrate species has shifted with the location of the Hamilton sewage treatment plant discharge. The toxicity existing in this region should be identified and corrected.

Heavy Metals in Sediments

Compared to other Great Lakes regions, high concentrations of lead, chromium, cadmium, mercury, and iron were found in the sediments, particularly, in the Randles Reef area (location 262). The sources of heavy metal discharges should be identified and some action taken to reduce these loadings.

Pesticides, Mercury and PCB Levels in Fish

With the exception of one White Bass, mercury levels in fish puree were less than 0.5 ppm. Predator fish like White Bass had levels of PCB greater than 5 ppm and as high as 11.7 ppm which is considered an unacceptable level. This indicates PCB discharges exist and should be identified and controlled. DDT levels in fish puree are lower than the breakdown products DDE and DDD indicating that recent DDT discharges are not a problem.

Trends

Ammonia levels in the harbour have dropped from a mean value of 6.9 mg/l in 1970 to 1.7 mg/l in 1972 due to control measures. The bottom fauna macroinvertebrate community has improved slightly in density and diversity between 1964-65 and 1972-73. Although chlorophyll a concentrations have remained approximately constant since 1966, phosphorus concentrations have increased slightly since 1968. Oxygen demands due to bottom sediments have increased over the years and the dissolved oxygen deficits in the hypolimnion are presently a problem.

RECOMMENDATIONS

The following recommendations are based on the premise that much of the harbour waters can be brought to a water quality standard that will be suitable for fish, wildlife and recreation. These recommendations are arranged in order of priority to achieve the required water quality enhancement.

The hypertrophic state and dissolved oxygen deficits are the most pressing water quality problems. If the harbour is to support fish and aquatic life or meet the provincial standards for aesthetics and recreation, these problems must be rectified. As the problem will probably require 10 to 20 years to correct, it is important that these steps be undertaken as soon as possible. It is recommended that:

1.   The concentrations of nutrients in the harbour be reduced by treatment.
2.   The principal chemical oxygen demand loadings be reduced by approximately 60 percent.
3.   Artificial destratification be considered as a means of reducing nutrient levels in the photic zone, oxidizing bottom sediments and preventing phosphorus from recycling.
4.   Aeration of the hypolimnion and selective sediment removal be investigated as a means of reducing the sediment oxygen demand.

If the harbour is to support fish and wildlife, it is important that the causes of toxicity to bottom fauna in the southeast portion of the harbour and the sources of heavy metal and PCB contamination be identified and rectified.

The present levels of bacterial contamination do not meet the water quality criteria for recreational use. If this use is contemplated for the harbour, the sources of bacterial contamination must be identified and rectified.

Landfilling is causing a local degradation of water quality. While the regions of the harbour affected by a degradation which violates the provincial criteria for fish and wildlife are small, it is advisable to curtail landfilling with the existing water quality problems in the harbour.

FURTHER STUDIES

Studies will be undertaken in 1974 to further amplify the findings of this report. As it is only possible to validate a two-dimensional numerical model in a dynamic system qualitatively, a three-dimensional model will be developed which will be validated by operating concurrently six installations, each consisting of one recording current meter and one water quality meter. The time histories of the major industrial outfalls will also be measured and

incorporated into the model and a non-conservative will be
modelled. The heavy metal sediment results will be analyti-
cally treated to relate sediment samples. As the oxygen
demand of the sediments is important, sediment demands will
be determined both in the laboratory and in the field at key
locations. Also, additional surveys will be undertaken to
identify bacti sources.

HAMILTON HARBOUR STUDY '74

section I

Proposed 1975
water quality surveys

1975 HAMILTON HARBOUR SURVEY PLAN

Hamilton Harbour is to be artificially mixed by aeration to relieve hypo-limnetic annoxia. A diffuser will be placed at the deepest point of the central basin to ensure complete vertical mixing of the water column. Combined with wind mixing and horizontal transport, it is likely that an oxidized microzone will be established and maintained at the sediment-water interface.

In conjunction with this project, a regular water and sediment quality survey of Hamilton Harbour during 1975 is desired. The purposes of this survey are as follows:

1. To determine the extent of mixing in the harbour.

2. To examine the effect of mixing on the bottom sediments, i.e., to determine the presence of an aerobic microzone.

3. To determine changes in the composition, abundance, and dist-ribution of fish and plankton.

4. To determine whether the epilimnetic nutrient concentration has been reduced.

5. To determine the effect of mixing on dissolved oxygen stock.

(a)   WATER QUALITY

A comprehensive water quality survey is to be undertaken with sampling performed at least biweekly from early April until commencement of mixing, and then weekly during the period of mixing, and biweekly from cessation of mixing until the end of October. Because of Great Lakes commitments, samples for bacti should be obtained on Tuesdays. The following stations and depths are to be employed.

Station	Latitude	Longitude	Depths to be Sampled (m)
4	43-17-11	79-48-00	0.2, 3.0, 6.0, 12.0, 18.0
252	43-18-20	79-48-40	0.2, 3.0, 6.0
258	43-17-20	79-50-10	0.2, 3.0, 6.0, 12.0, 20.0
270	43-16-50	79-52-20	0.2, 3.0, 6.0, 12.0

Locations of the sampling stations and the propsed diffuser location are shown in Figure 1. Station 4 was used in the 1967 survey and is in the deep hole immediately west of station 251. Station 270 is immediately northeast of station 265 and is selected for a greater available depth. Prior to sampling, the presence of an adequate water depth should be ascertained, and if such is not present, the sampling vessel should move to a location which provides sufficient depth.

Depth profiles of temperature and dissolved oxygen are to be obtained weekly at each station.

The following chemical parameters are to be determined on all samples:

Conductivity
pH
Turbidity
Ammonia
Total Kjeldahl Nitrogen
Nitrite
Nitrate
Total Phosphorus
Soluble Phosphorus
Dissolved Reactive Silicates
Alkalinity
Iron
Chlorophyll

The following parameters are to be determined on the surface and bottom samples at each station:

COD
BOD
TOC
Total Coliforms
Fecal Coliforms
Enterococci
Sulfur Cycle Bacteria
Nitrifiers
Total heterotrophic Bacteria
Pseudomonads
Sodium (monthly only)
Potassium (monthly only)
Calcium (monthly only)
Magnesium (monthly only)
Chloride (monthly only)
Sulphate (monthly only)

Total and soluble fractions of the following heavy metals are to be done monthly. Two depth composites for each station,one filtered in the field, are to be collected, using equal volumes of water from each of the above indicated depths:

Chromium
Manganese
Cobalt
Nickel
Copper
Zinc
Cadmium
Mercury
Molybdenum
Lead

Pesticides and PCB's are also to be determined on similar monthly depth composite samples.

For purposes of nutrient and dissolved oxygen trend studies, monthly samples will be collected by the Lake Systems group on calm days. At the 17 station grid as used in 1972, temperature and dissolved oxygen-depth profiles are to be taken. Bathythermograph casts and dissolved oxygen meters will be used if possible, to simplify data collections. Nutrient samples will be taken at the surface and bottom from the 8 station subset used intensively in 1972.

(b)   SEDIMENT CHEMISTRY

Sediment samples are to be taken by dredge once before mixing is initiated and at least once after mixing has started. In order to locate areas of greatest oxygen demand and discern areas of related sediment quality, a set of 20 stations should be sampled: (Figure 2)

Stations: 4,15,20,252,253,254,255,256,257,258,259,260,261,262,263,
               264,268,269,270 and 1030.

Stations 4 and 270 are as above and replace stations 251 and 265 respectively. The following parameters should be determined on all cores:

BOD
COD
TOC
Loss on ignition
Total Kjeldahl N
Total Phosphorus
Acid-extractable Phosphorus

PCB
Chromium
Manganese
Iron
Cobalt
Nickel
Copper
Zinc
Cadmium
Mercury
Molybdenum
Lead

An attempt should be made to measure redox potential of the sediment as a function of sediment depth up to 20 cm below the sediment-water interface. Temperature, dissolved oxygen and conductivity of the water immediately above the sediment should be measured if possible.

(c)   PHYTOPLANKTON AND ZOOPLANKTON

A biological survey by a University contract will compliment the Hamilton Harbour Study 1975. Phytoplankton enumeration and identification, primary productivity, and bioassays will form the bulk of the biological work. The four stations will be sampled at three depths to correspond with the water quality survey.

Zooplankton work should be simple, consisting of a vertical net haul through the entire water column at all stations. Relative species abundance should be determined, and total population size represented as dry weight. Diurnal migrations in the vertical and horizontal plane result in difficulties in deter-mining spatial distribution of zooplankton; thus more emphasis should be placed on seasonal changes within the period of observation.

Zooplankton grazing experiments and/or analyses of gut contents to deter-mine selective feeding on the phytoplankton is important.

The attached sheet outlines the biological survey to be done by contract. Station composites should be collected by M.O.E. (100 ml sample) and pre-served in Lugol's Iodine. Cell measurements, enumeration and identification will be done as a parallel study to determine phytoplankton biomass and species diversity.

(d)   BOTTOM FAUNA

Bottom fauna (composition and abundance) should be collected using an Ekman bottom grab sampler. Collections should be made at the same time sediment samples are collected for chemical analysis. The should be at the 20 locations used for the sediment analysis, for comparison with previous studies and provide estimates of the effect of bottom fauna on sediment oxygen uptake.

Invertebrates should be separated from the sediment by washing through a sieve with 0.65 mm apertures, and preserved in ethanol.

As background data is available, increased sampling frequency would be of value to determine community structure and diversity during 1975. This however, is not essential, but would help determine factors affecting the bottom fauna composition and abundance.

(e)   FISH SURVEY

Perhaps one of the first biological responses to aeration will be changes in the relative abundance, distribution and composition of the fish populations of Hamilton Harbour. At least two nettings, before and after mixing, are required at the four sampling stations. Some fish will be collected for flesh analyses (heavy metals, pesticides, P.C.B.). It is hoped that the Ministry of Natural Resources will do the nettings.

BIOLOGICAL SURVEY

HAMILTON HARBOUR 1975

Biological responses to mixing are to be determined by
sampling at weekly intervals at four stations. Volume
samples will be collected at three depths, representative of
the top, middle and bottom of the water column. Phytoplank-
ton identification and enumeration will be determined for
all samples. Chlorophyll - a will also be determined for
each sample.

Temperature and dissolved oxygen profiles will be measured
at the time of sampling for each station. Vertical net
hauls through the water column using a 60 μm mesh will be
used to estimate zooplankton crops.

Primary productivity experiments using the light and dark
bottle technique will be accompanied by measurements of the
vertical attenuation of solar radiation to form an essential
component of this study. Combined with simple bioassay
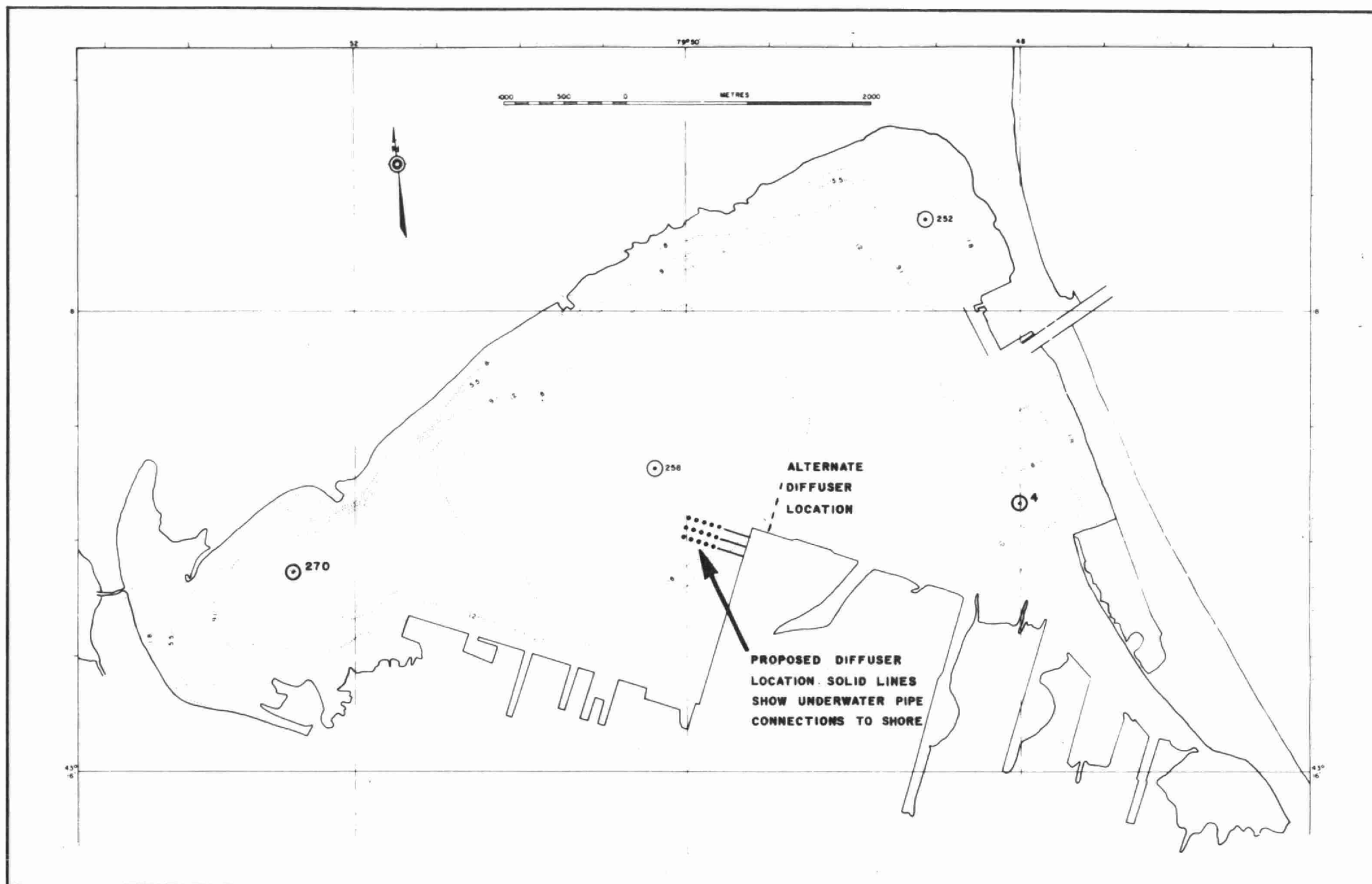studies the production potential of the harbour can be
determined.

FIG. 1 PROPOSED WATER QUALITY SAMPLING STATIONS, 1975.

FIG. 2 PROPOSED SEDIMENT SAMPLING STATIONS, 1975.